Breaching the blendwall: RINs and the market for renewable fuel

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Abstract

Two peculiar features of the market for renewable fuel are essential for understanding the welfare consequences of the Renewable Fuel Standard (RFS). First, the 10% limit on ethanol in E10 gasoline—the blendwall—makes the total renewable fuel mandate more costly. Second, the linkage among prices of different categories of renewable energy credits—RINs—makes the total renewable fuel mandate less costly. I simulate policy experiments in a model that captures both of these features. In the short run, I find that reducing carbon emissions using the RFS imposes welfare costs of more than $300 per metric ton of CO_2.

Keywords: Biofuel Policy, RFS, RIN, Blendwall, Tradeable Credit

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1 Introduction

The Renewable Fuel Standard (RFS) is one of many potential policy tools for fighting climate change. The RFS requires American drivers to consume a minimum amount of renewable fuel as a method

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of displacing petroleum-based fuel with biomass-based fuel and thereby reducing carbon emissions. The RFS minimum volume requirement that was scheduled by law in 2007 is reevaluated annually by the Environmental Protection Agency (EPA). The EPA can stick with the original RFS schedule or reduce the RFS volumes by some amount.

This paper simulates policy alternatives with a real-world policy tool controlled by the EPA—the RFS minimum volume requirement—in a model that captures two important features of the market for renewable fuel: the blendwall, and the RFS linkage between ethanol and biodiesel. These two features are typically absent from welfare analysis of renewable fuel mandates.[1] With the linkage between ethanol and biodiesel, marginal increases in the RFS mandate beyond the blendwall are filled by a combination of biodiesel and E85. I find that both biodiesel and E85 are expensive methods of reducing carbon emissions.

Through its implementation of the RFS, the EPA currently requires American drivers to consume more renewable fuel than can be blended into the most common gasoline blend. The 10% limit on ethanol in E10 gasoline is called the blendwall. The infrastructure for distributing and consuming regular gasoline cannot accommodate a blend with more than 10% ethanol because ethanol is more corrosive than petroleum-based gasoline. When the RFS minimum volume requirement was below the blendwall, meeting the requirement was easy because it could be done simply by adding more ethanol to E10 gasoline.

Now that the RFS requirement exceeds the blendwall, the only way to meet the requirement is by increasing consumption of renewable fuels other than ethanol in E10 gasoline. The RFS makes distinctions among good and better renewable fuels. It sets minimum volumes in four separate categories, each of which has its own renewable energy credit (RIN). The RFS allows "better" renewable

[1] De Gorter and Just (2009), Lapan and Moschini (2012), Cui, Lapan, Moschini, and Cooper (2011), Holland, Hughes, Knittel, and Parker (2013), and Chen, Huang, Khanna, and Önal (2014) all performed welfare analysis on renewable fuel mandates without incorporating the blendwall or the RFS linkage between ethanol and biodiesel.

fuels—like biodiesel—to satisfy requirements in place of "good" renewable fuels—like corn ethanol. So even though the minimum volume requirement for ethanol exceeds 10% of E10 gasoline, that requirement can be met with biodiesel or other gasoline blends.

The model includes salient features of markets related to renewable fuel. Consumers demand diesel, gasoline, and nonfuel corn. Producers supply renewable and nonrenewable blending components for gasoline and diesel. Fuel blenders combine blending components into blended fuel. The RFS requirements are modeled by incorporating RIN prices into the decision problem of blenders. I solve for a perfectly competitive equilibrium.

I calibrate the model to make the simulations empirically relevant. I use supply and demand elasticities estimated from prior literature, and I use data to calibrate remaining parameters. The calibrated model does a good job matching untargeted moments.

The simulation indicates the RFS is a costly method of reducing carbon emissions in the short run. I find that reducing carbon emissions using the RFS imposes welfare costs of more than \$300 per metric ton of CO_2. The linkage between ethanol and biodiesel mitigates the cost of reducing emissions with the RFS relative to a world in which the entire reduction occured through E85. However, both biodiesel and E85 are expensive ways to reduce carbon emissions.

Biodiesel is an expensive way to reduce carbon emissions because (1) it has a steep supply curve and (2) as an input it is a very good substitute with petroleum-based diesel. The blender cost of petroleum diesel must rise along with the blender cost of biodiesel in order for biodiesel to remain competitive as an input, and the blender cost of petroleum diesel is not easily moved. E85 is an expensive way to reduce carbon emissions because (1) consumers require a substantial discount to substitute E85 for E10 consumption and (2) ethanol is a modest reduction in emissions relative to BOB, the fuel it displaces. Corn ethanol emits almost as much carbon as petroleum-based gasoline, so the reduction in carbon emissions is small relative to the welfare loss from distorting consumption of food and fuel.

The RFS is not a good tool for reducing carbon emissions in the short run, but it might be a good tool in the long run. Legislators hoped the RFS would support a massive expansion in cellulosic ethanol, which is a large reduction in carbon emissions relative to petroleum-based gasoline. The RFS could be useful as a tool for developing cellulosic ethanol technology and expanding infrastructure for consuming cellulosic ethanol in E85. However, the dynamic effects of the RFS are beyond the scope of this paper.

The peculiar features of the RFS and the markets for blended fuel are described in section 2. I present a model in section 3, test price predictions of the model in section 4, calibrate the model in section 5, present the results of a policy simulation in section 6, and conclude in section 7.

2 Institutional context

2.1 Blended fuel

Transportation fuel is a blend of renewable and nonrenewable fuel. Gasoline is a blend of ethanol (renewable) and petroleum-based gasoline (nonrenewable). Similarly, diesel is a blend of biodiesel and petroleum-based diesel. Blenders combine these blending components into blended fuels. Three blended fuels are important for understanding the Renewable Fuel Standard (RFS): E10 gasoline, which contains 0% to 10% ethanol; E85 gasoline, which contains 51% to 85% ethanol; and blended diesel.[2]

Gasoline—Ethanol is an imperfect substitute for petroleum-based gasoline, also called blendstock for oxygenate blending or BOB when it is an input into blended gasoline, because it has a lower energy

[2]It would be more precise to say that E85 contains at most 83% ethanol, because in high blends at least 2% of the ethanol portion must be denaturant (Alternative Fuels Data Center, 2013b). According to the EPA, the average ethanol fraction in E85 is 71%. In some seasons and regions of the country, the practical limit on ethanol is substantially below 85% to avoid cold start problems. Other blends of gasoline exist but are unlikely to be relevant to policy in the near term. For example, E15 gasoline contains 15% ethanol. As of January 2014, there were only 59 stations in the United States vending E15 (Renewable Fuels Association, 2014).

content and a higher octane rating. Octane is a measure of the compression a fuel can withstand before detonating. If two fuels have equal energy content but one has a higher octane rating, the one with a higher octane rating performs better, in the sense that it gets more miles per gallon. Octane improves fuel performance with diminishing returns. Adding ethanol into a gasoline blend with low octane improves performance because the high-octane effect dominates the low-energy effect. Adding ethanol into a gasoline blend with high octane hinders performance because the low-energy effect dominates the high-octane effect. Gasoline is required to have an octane rating above the octane rating of BOB. If BOB is not blended with ethanol, other octane-boosting liquids must be added to BOB in order to comply with the minimum octane rating.[3]

Ethanol is also different from BOB because ethanol is more corrosive. Containers designed for petroleum gasoline, including underground tanks at gas stations and gas engines in light-duty vehicles, do not need to be modified to use E10. E85 can damage those containers and cause leaks.

Demand for E85 and demand for E10 are derived from demand for vehicle miles traveled. The relative demand for E85 depends on the rate at which drivers substitute E85 for E10. This substitution can be made safely by drivers of flex fuel vehicles (FFVs). FFVs accept a wide range of gasoline blends including both E10 and E85. Most gasoline-powered vehicles can be converted to accept E85 for $200-$400,[4] but the current fleet of 226 million vehicles includes just 12 million FFVs.[5] As a result of the differences in octane and energy content between ethanol and BOB, a car travels farther on one gallon of E10 than on one gallon of E85.

All else equal we expect consumers to choose the blend that enables more miles per dollar, but miles per dollar is not the only consideration. The lower energy content of E85 requires drivers to fill

[3] In the 1990s and early 2000s, many suppliers raised the octane rating of gasoline by adding methyl-tertiary butyl ether (MTBE). Because ethanol also raises the octane rating of gasoline, it is a substitute for the energy content of BOB and the octane rating of MTBE. Ethanol blending jumped in 2006 as a result of the ban on MTBE (Anderson and Elzinga, 2014).

[4] Change2e85.com sells conversion kits for 4- and 6-cylinder engines for $199 and $325.

[5] Energy Information Administration, Annual Energy Outlook, 2013, Table 58: "Light-Duty Vehicle Stock by Technology Type".

their tanks more frequently. The three thousand E85 stations in the United States are much sparser than the hundreds of thousands of E10 stations, so filling a gas tank with E85 is often inconvenient. Some FFV owners are not even aware their vehicles accept E85. Yet drivers purchased E85 in small volumes even when E85 was more expensive than E10 per gallon and far more expensive per mile.

Diesel—Biodiesel is an excellent substitute for petroleum-based diesel. The energy content of biodiesel is nearly as high as the energy content of petroleum-based diesel. Biodiesel may reduce performance if it is stored in high blends for long periods in cold weather, but for most drivers, the performance of blends with 5% biodiesel or less is the same as 100% petroleum-based diesel. The average blend of biodiesel in diesel has always been below 3%.

Biodiesel production is limited by competition with petroleum-based diesel as an input into blended diesel. Diesel blenders choose a blend composition that minimizes cost. Because blends with low biodiesel content are nearly perfect substitutes and the average blend of 2% in 2013 includes both biodiesel and petroleum-based diesel, the blender cost of biodiesel must nearly equal the blender cost of petroleum-based diesel. The blender cost of components includes explicit and implicit taxes and subsidies, including those from the RFS.

2.2 The Renewable Fuel Standard

The Energy Independence and Security Act of 2007 (EISA) set a schedule of aggregate minimum volume requirements for annual consumption of renewable fuel. The minimum volumes in EISA and their implementation by the Environmental Protection Agency (EPA) are called the Renewable Fuel Standard (RFS). Every year, the EPA translates the RFS minimum volume requirement into an obligation on individual refiners in proportion to the volume of nonrenewable fuel they refine. For example, if the RFS minimum renewable volume was 10 billion gallons, and nonrenewable fuel consumption was expected to be 100 billion gallons, then the EPA would require refiners to prove use of 0.1 gallon of renewable fuel for every gallon of nonrenewable fuel they refined.[6] That fraction, 0.1, is the policy tool controlled by the EPA. It expresses the obligation faced by a refiner per gallon of nonrenewable fuel.

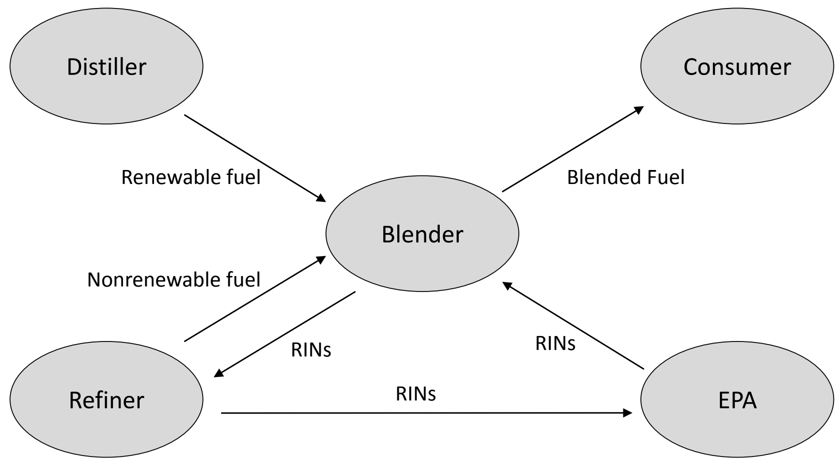
To keep track of RFS compliance, the EPA created Renewable Identification Numbers (RINs). RINs are renewable energy credits "generated" when renewable fuel is added to a fuel blend, meaning the EPA gives RINs to the blender. RINs generated by blenders are the supply of RINs, and RFS obligations on refiners are the demand for RINs. A blender who generates RINs can sell them to a refiner, who must submit RINs to the EPA to prove compliance with the RFS. Thus a RIN is received from the EPA by a blender, sold to a refiner, and submitted back to the EPA. Figure 1 illustrates the flow of blending components to the blender, the flow of blended fuel to the consumer, and the flow of RINs.

The treatment of a gallon of renewable fuel under the RFS depends on the raw material—feedstock—that is used to produce that gallon. There are four renewable fuel categories under the RFS: cellulosic, biodiesel, advanced, and renewable. The eligibility of a feedstock for a RIN category depends on the EPA's assessment of the life cycle greenhouse gas emissions of renewable fuel produced from that feedstock relative to the nonrenewable fuel it displaces.[7] There are four categories of RINs corresponding to the four categories of renewable fuel under the RFS. One ethanol-equivalent gallon is the standard unit of RINs. For one gallon of grain corn ethanol, the blender generates one RIN. Other renewable fuels generate different volumes of ethanol-equivalent gallons; one gallon of biodiesel produces 1.5 ethanol-equivalent RINs. Cellulosic and biodiesel are mutually exclusive subsets of advanced, and advanced is a subset of renewable.

[6] In the example, the fraction 0.1 is equal to $\frac{\text{10 billion gallons of renewable fuel}}{\text{100 billion gallons of nonrenewable fuel}}$.

[7] The EPA determined that the life cycle greenhouse gas emissions from grain corn ethanol are 20% below petroleum-based gasoline, so grain corn ethanol is eligible to produce renewable RINs. The reduction thresholds for the EPA to allow an ethanol feedstock to generate advanced and cellulosic RINs are 50% and 80% relative to petroleum-based gasoline. To produce a biodiesel RIN, a biodiesel feedstock must reduce life cycle greenhouse gas emissions 50% relative to petroleum-based diesel.

Figure 1: Flow of fuel and RINs



Note: Renewable fuel includes ethanol and biodiesel. Nonrenewable fuel includes BOB and petroleum-based diesel. Blended fuel includes E10, E85, and B5. The EPA gives RINs to a blender when the blender adds renewable fuel to a blend. The blender sells RINs to a refiner. The refiner submits RINs back to the EPA to demonstrate compliance with the RFS.

A gallon of petroleum-based gasoline incurs the same obligation as a gallon of petroleum-based diesel. For each gallon of nonrenewable fuel, a refiner must submit a fraction of a RIN from all four RIN categories: a fraction of a cellulosic RIN (ρ_3), a fraction of a biodiesel RIN (ρ_4), a fraction of an advanced RIN (ρ_5), and a fraction of a renewable RIN (ρ_6). Because cellulosic and biodiesel are subsets of advanced, the fraction ρ_5 is the *residual* fraction of an advanced RIN. If a refiner submits biodiesel RINs in excess of the biodiesel fraction, it has less residual obligation. Similarly, ρ_6 is the *residual* fraction of a renewable RIN. The subscripts on the ρ fractions correspond to the labels typically used by the EPA to denote the four renewable fuel categories.

The mandate fractions $(\rho_3, \rho_4, \rho_5, \rho_6)$ are the policy tool controlled by the EPA. In an RFS rule released annually, the EPA calculates the mandate fractions as the renewable volume requirements in EISA divided by total nonrenewable volume forecast by the Energy Information Administration. EISA grants waiver authority to the EPA to adjust this calculation under some circumstances.[8] The main policy adjustment I consider is the renewable volume requirement (ρ_6).

[8]In the past, some RFS rules exempted certain nonrenewable producers from obligations under the mandate. Other RFS rules reduced the cellulosic volume requirement in recognition of inadequate domestic supply.

RINs can be traded and stored, but there are some constraints on storage. An RFS obligation may only be filled with RINs generated in the same year and one year prior, and at most 20% may be filled with prior-year RINs. However, the aggregate stock of RINs is estimated to be around 2.6 billion, well below 20% of the total renewable mandate, so the restriction to prior-year RINs just means that the existing stock of prior-year RINs should be used for compliance and exhausted before tapping into current-year RINs. RINs of different vintages are thus good substitutes.

The RFS minimum volumes are based on the 2007 law and adjusted by the EPA to accomodate unforeseen circumstances. In 2013, the EPA reduced the cellulosic volume from 1 *billion* gallons, as scheduled back in 2007 by EISA, to 6 *million* gallons in recognition of inadequate supply. The capacity to produce cellulosic fuel has lagged far behind the timetable set in EISA.

Table 1: Renewable fuel mandated by RFS

RIN obligation per gallon of nonrenewable						
Year	**Cellulosic**	**Biodiesel**	**Advanced**	**Subtotal**	**Renewable**	**Total**
2010	0.00%	0.62%	0.00%	0.63%	7.62%	8.25%
2011	0.00%	0.69%	0.08%	0.78%	7.24%	8.01%
2012	0.00%	0.91%	0.30%	1.21%	8.02%	9.23%
2013	0.00%	1.12%	0.48%	1.60%	8.03%	9.63%
2014	0.01%	1.16%	0.16%	1.33%	7.87%	9.20%

Note: This table shows the fraction of a RIN an obligated party must submit per gallon of nonrenewable. The fraction for advanced is a residual eligible to be filled by non-cellulosic, non-biodiesel advanced. Similarly, the fraction for renewable is a residual eligible to be filled by non-advanced renewable. Fractions for 2013 and earlier are from final EPA rules. 2014 fractions are from the EPA notice of proposed rulemaking. The 2012 cellulosic fraction was reduced to zero by court order. The biodiesel fraction from the final 2010 rule is distributed partially to 2009. Schnepf and Yacobucci (2013).

The EPA computes the RIN obligation per gallon of nonrenewable as a fraction, where the numerator is the minimum renewable volume and the denominator is the expected volume of nonrenewables forecast by the Energy Information Administration (EIA). In 2013, the EPA set the minimum total renewable volume (including cellulosic, biodiesel, and advanced) at 16.55 billion ethanol-equivalent gallons. The EIA forecast nonrenewable volume of 172 billion gallons. So the total renewable mandate fraction was 9.63% ($= \frac{16.55}{172}$), which is the fraction of ethanol-equivalent RINs that must be submitted by a refiner for each gallon of nonrenewable.[9] Table 1 shows the actual RFS fractions from 2010 to 2013 and the proposed fractions for 2014.

2.3 RIN prices

The prices of the four categories of RINs are related through several mechanisms. The price of an advanced RIN should be at least as high as the price of a renewable RIN. This is because, under the RFS, an advanced RIN can be used to satisfy the renewable obligation. If advanced RINs were cheaper than renewable RINs, an obligated party would be better off purchasing advanced RINs to satisfy its renewable obligation. Similarly, the price of an advanced RIN should be no higher than the price of a biodiesel RIN. This inequality is not an explicit rule; it is a logical consequence. The RFS places complex constraints on the price of cellulosic RINs. They are usually pinned to the price of advanced RINs plus 25 cents.

Most renewable RINs are produced by blending domestic corn ethanol. Most advanced RINs are produced by blending sugarcane ethanol from Brazil. Brazilians are indifferent between sugarcane ethanol and corn ethanol because the performance of fuel made from the two feedstocks is identical, but American blenders are not indifferent because the price of a sugarcane ethanol RIN can differ from the price of a corn ethanol RIN. The transportation cost of a round trip to exchange American corn ethanol for Brazilian sugarcane ethanol is around 40 cents per gallon. Therefore, arbitrage constrains the amount by which the price of advanced RINs can exceed the price of renewable RINs to 40 cents.

[9] In 2013, a refiner that produced 100,000 gallons of BOB would be in compliance with the RFS mandate if it submitted 3 cellulosic RINs generated from 3 gallons of switchgrass ethanol; 1,120 ethanol-equivalent biodiesel RINs generated from 747 gallons of biodiesel; 480 advanced RINs generated from 480 gallons of sugarcane ethanol; and 8,030 renewable RINs generated from 8,030 gallons of grain corn ethanol.

The price of RINs changes the blender cost of components. When a blender purchases a gallon of ethanol, it also gets to sell the RIN it generates from blending that gallon. The blender cost of ethanol is the price the blender pays for the ethanol minus the price it receives for selling the RIN. In this way, RINs act like a subsidy to renewable fuel because a blender earns revenue from selling a RIN. Similarly, the blender cost of BOB is higher than the world price of BOB because RINs act like a tax on BOB in the United States.[10]

2.4 The blendwall

I will use the term "blendwall" to mean 10% of blended gasoline. This differs slightly from the typical meaning of blendwall—the volume of ethanol that "can" be incorporated into the fuel supply as a component of blended gasoline.[11] This typical meaning of blendwall is not well defined. The volume that is incorporated into blended gasoline is sensitive to prices and infrastructure, both of which are changing in response to the RFS. Expectations about the RFS influence the decision to vend E85 at a gas station or to buy a flex fuel vehicle.[12] This definition of blendwall thus depends on the policy we are trying to analyze. A benchmark of 10% of gasoline consumption provides a stable point of reference, so I use this definition of blendwall.

In 2013, the minimum RFS volume exceeded the blendwall.[13] Until 2013, RFS compliance could be achieved by increasing the fraction of ethanol in E10 gasoline.[14] That method of compliance has

[10] Lade, Lin, and Smith (2015) explain the following benchmark for RIN prices: "RIN prices equal the weighted difference between the cost of the marginal ... renewable fuel used to meet each mandate and the marginal cost of the cheaper fossil fuel it displaces." This benchmark for RIN prices can be violated through the linkage between the price of a cellulosic RIN and an advanced RIN, the arbitrage relationship between the price of an advanced RIN and the price of a conventional RIN, and the technical constraint on blending ethanol into E10.

[11] A less common meaning of blendwall is the highest EPA-permitted blend fraction, which the EPA lifted from 10% to 15% in 2010 for most vehicles. Qiu, Colson, and Wetzstein (2014) use this definition.

[12] Babcock (2013) simulates the response of investment in E85 infrastructure to the RFS. Du and Carriquiry (2013) examine the impact of expanding the share of FFVs on ethanol price dynamics. Du and Li (2015) examine the impact of E85 fueling stations on the market share of FFVs.

[13] 14.63 billion gallons were eligible to be satisfied by ethanol. Even if the 132.8 billion gallons of gasoline consumption forecast by the EIA included 10% ethanol, the volume of ethanol consumed would still fall 1.35 billion gallons short of satisfying the mandate.

[14] Online appendix Table 6 shows that from 2006 to 2013, the average blend in E10 increased from 4% to 10%. Online appendix Figure 8 shows that the mandate schedule passes the blendwall because it follows the trajectory of

reached its limit; renewable fuel must be added to the fuel supply in some way other than increasing the fraction of ethanol in E10. There are four options for generating additional RINs once the ethanol fraction of E10 gasoline has reached its limit: increase the volume of E10 gasoline, increase the ethanol fraction in E85 gasoline, increase the volume of E85 gasoline, and increase the biodiesel fraction in blended diesel.

The response of the market to the tension between the blendwall and RFS volumes hinges on demand for E85 gasoline and supply of biodiesel. We know a little bit about the demand for E85 from prior literature.[15] However, the quantity of E85 and the quantity of biodiesel are in uncharted territory, and if the mandate increases according to its schedule, they will continue to break new ground.

3 Model

I build a model to serve as a laboratory for experimenting with policy options available to the Environmental Protection Agency (EPA) for implementing the Renewable Fuel Standard (RFS). The blender buys blending components from suppliers and sells blended fuel to consumers. The RFS mandate is incorporated into the blender's decision problem.

There is one biofuel in the model for each of the three categories of RINs that are produced in quantities large enough to affect the blendwall: biodiesel generates biodiesel RINs, sugarcane ethanol generates advanced RINs, and corn ethanol generates renewable RINs. The price of cellulosic RINs is set equal to the price of advanced RINs plus 25 cents.

gasoline consumption that was expected when the law passed in 2007.

[15] Du and Carriquiry (2013) and Du and Li (2015) examine the impact of expanding the share of FFVs and the number of E85 fueling stations. Anderson (2012) uses fuel-station level data in Minnesota to estimate a discrete choice model in which consumers value E85 directly in addition to its use for vehicle miles traveled. Liu and Greene (2013) and Pouliot and Babcock (2014) estimate similar discrete choice models.

3.1 Consumers

Utility is quasilinear in three goods: gasoline miles (G), diesel miles (BX), and bushels of nonfuel corn (C), each of which has a constant elasticity of demand (ϵ_i). Consumers have a standard budget constraint with income Y, and the price of the numeraire (Z) is normalized to 1. Diesel miles are traveled using a single average diesel blend. Gasoline miles are traveled using a combination of E10 gasoline and E85 gasoline. The elasticity of substitution between E10 and E85 is $\frac{\sigma}{1-\sigma}$, and the demand share of E10 is α.

$$
\begin{aligned}
\max_{Q_{E10},Q_{E85},Q_{BX},Q_C,Q_Z} \quad & \phi_G \frac{\left[(\alpha)(Q_{E10})^{\frac{1}{\sigma}} + (1-\alpha)(\gamma Q_{E85})^{\frac{1}{\sigma}}\right]^{(\sigma)(1-\frac{1}{\epsilon G})}}{1-\frac{1}{\epsilon G}} \\
& + \phi_B \frac{Q_{BX}^{1-\frac{1}{\epsilon B}}}{1-\frac{1}{\epsilon B}} + \phi_C \frac{Q_C^{1-\frac{1}{\epsilon C}}}{1-\frac{1}{\epsilon C}} + Q_Z \\
s.t. \quad & P_{E10}Q_{E10} + P_{E85}Q_{E85} + P_{BX}Q_{BX} + P_C Q_C + Q_Z = Y
\end{aligned} \tag{1}
$$

Because there is a numeraire good, there is no income effect of price changes in fuel and nonfuel corn. The first order conditions imply the relative demand of E85 is a function of the relative price of E85. Consumers demand more E85 when it is cheaper relative to E10.

$$
\frac{Q_{E85}}{Q_{E10}} = \left(\frac{P_{E85}}{P_{E10}}\right)^{\frac{\sigma}{1-\sigma}} \left(\gamma\right)^{\frac{1}{\sigma-1}} \left(\frac{1}{\alpha}-1\right)^{\frac{\sigma}{\sigma-1}} \tag{2}
$$

Nonfuel corn is included in the model to facilitate calibration. It permits use of outside estimates of the elasticity of supply for corn and the elasticity of demand for corn, so that the elasticity of supply for corn as fuel arises endogenously through the decision of the corn producer.[16] In the model,

[16] An alternative approach would be to leave nonfuel corn out of the model and use an outside estimate of the elasticity of ethanol supply, such as by Luchansky and Monks (2009). Because corn ethanol is such a large part of the RFS and the market for corn, I believe the benefit of explicitly modeling the tradeoff with nonfuel corn is worth the added complexity. Several studies have gone further in this direction to examine the effect of the biofuel mandates on food and fuel prices. Wu and Langpap (2014) find that the RFS raised corn prices substantially with a small positive

nonfuel corn is sold directly by the corn producer to consumers, whereas fuel passes through blenders of E10, E85, and diesel. The first order conditions imply demand curves for gasoline, diesel, and nonfuel corn.

$$P_{E10} = \phi_G[(\alpha)(Q_{E10})^{\frac{1}{\sigma}} + (1-\alpha)(\gamma Q_{E85})^{\frac{1}{\sigma}}]^{\sigma - \frac{\sigma}{\epsilon G} - 1} Q_{E10}^{(\frac{1-\sigma}{\sigma})}(\alpha) \tag{3}$$

$$P_{BX} = \phi_B Q_{BX}^{-\frac{1}{\epsilon B}} \tag{4}$$

$$P_C = \phi_C Q_C^{-\frac{1}{\epsilon C}} \tag{5}$$

3.2 Suppliers

Supply of corn ethanol and nonfuel corn—The corn producer maximizes profit by choosing ethanol ($E100$) and nonfuel corn (C). Nonfuel corn can be converted to ethanol at a fixed ratio μ. Costs are an increasing function of the number of bushels of corn required to produce the ethanol and nonfuel corn ($Q_C + \mu Q_{E100}$). The first order condition for corn gives the corn supply curve with constant supply elasticity ηC. The first order condition for ethanol implies a relationship between the price of ethanol and nonfuel corn.

$$\max_{Q_C, Q_{E100}} \qquad P_C Q_C + (P_{E100} - \nu_C) Q_{E100} - \theta_C \frac{(Q_C + \mu Q_{E100})^{1+\frac{1}{\eta C}}}{1 + \frac{1}{\eta C}}$$

FOCs imply: $$P_C = \theta_C (Q_C + \mu Q_{E100})^{\frac{1}{\eta C}} \tag{6}$$

$$P_{E100} = \mu P_C + \nu_C \tag{7}$$

impact on food prices overall and a small negative impact on gasoline prices. McPhail and Babcock (2012), who model the blendwall, find that the RFS increases price variability.

ν_C is the markup of the price of ethanol over the price of corn inputs. It reflects the cost of distillation and the revenue received from byproducts of distillation like dried distillers grains.

Supply of petroleum-based gasoline and diesel—The petroleum gasoline refiner chooses the quantity of gasoline blendstock for oxygenate blending ($E0$) to maximize profit. The first order condition implies a supply curve with intercept θ_G and constant elasticity ηG.

$$\begin{aligned} &\max_{Q_{E0}} && P_{E0}Q_{E0} - \theta_G \frac{Q_{E0}^{1+\frac{1}{\eta G}}}{1+\frac{1}{\eta G}} \\ &\text{FOC implies:} && P_{E0} = \theta_G Q_{E0}^{\frac{1}{\eta G}} \end{aligned} \tag{8}$$

The diesel refiner's problem is parallel to the gasoline refiner's problem. The petroleum diesel refiner chooses the quantity of petroleum-based diesel ($B0$) to maximize profit. The first order condition implies a supply curve with intercept θ_D and constant elasticity ηD.

Supply of biodiesel—The biodiesel refiner chooses the quantity of biodiesel ($B100$) to maximize profit. The biodiesel refiner pays a constant marginal cost (ν_B) for the biodiesel feedstock, and faces increasing marginal costs of refining. The biodiesel refiner's first order condition implies a supply curve.

$$\begin{aligned} &\max_{Q_{B0}} && P_{B100}Q_{B100} - \nu_B Q_{B100} - \theta_B \frac{Q_{B100}^{1+\frac{1}{\eta B}}}{1+\frac{1}{\eta B}} \\ &\text{FOC implies:} && P_{B100} = \nu_B + \theta_B Q_{B100}^{\frac{1}{\eta B}} \end{aligned} \tag{9}$$

Supply of sugarcane ethanol—The sugarcane ethanol supplier chooses the quantity of sugarcane ethanol (Q^S_{E100}) to maximize profit. The sugarcane ethanol supplier's first order condition implies a supply curve.

$$\max_{Q^S_{E100}} \quad P^S_{E100}Q^S_{E100} - \theta_S \frac{(Q^S_{E100})^{1+\frac{1}{\eta S}}}{1+\frac{1}{\eta S}}$$

$$\text{FOC implies:} \quad P^S_{E100} = \theta_S (Q^S_{E100})^{\frac{1}{\eta S}} \tag{10}$$

3.3 Blender

The blender of E10 gasoline chooses the quantity of E10 gasoline and the fraction of ethanol in each blended gallon (F_{E10}) to maximize profit. I use the shorthand ρ as a row vector of mandate fractions and P_{RIN} as a column vector of RIN prices such that the obligation per gallon in dollars is ρP_{RIN}: $\rho P_{RIN} \equiv \rho_3 P_{R3} + \rho_4 P_{R4} + \rho_5 P_{R5} + \rho_6 P_{R6}$.[17]

$$\max_{Q_{E10}, F_{E10}} \quad Q_{E10}\Big[P_{E10} - F_{E10}\big(P_{E100} - P_{R6}\big) - (1 - F_{E10})(P_{E0} + \rho P_{RIN})\Big]$$

$$s.t. \quad 0 \leq F_{E10} \leq 0.1$$

Profit is equal to the volume of E10 gasoline times the difference between the price received by the blender (P_{E10}) and the blender cost of components. The wholesale price of ethanol is offset by the generation and sale of a RIN, so the blender cost of ethanol is $P_{E100} - P_{R6}$. The wholesale price of BOB is augmented by the cost of RFS compliance, so the blender cost of BOB is $P_{E0} + \rho P_{RIN}$.

The quantity first order condition expresses an arbitrage condition that relates the price of blended E10 gasoline to the cost of components.[18] The fraction first order condition says that, if the blend fraction is at an interior solution above 0% and below 10%, then the blender cost of ethanol must equal the blender cost of BOB. The blender of E85 gasoline and blended diesel face analogous problems.

[17] Fractions and RIN prices are indexed by numbers 3 to 6, which the EPA associates with cellulosic, biodiesel, advanced, and renewable RINs.

[18] When the model is calibrated, the arbitrage condition will also include a wedge between the price of blended fuel and the blender cost of components to account for transportation costs and taxes. See section 4.

Their quantity and fraction first order conditions express parallel relationships between price and blender cost, and between the cost of one component and the other.[19]

$$P_{E10} = F_{E10}(P_{E100} - P_{R6}) + (1 - F_{E10})(P_{E0} + \rho P_{RIN}) \tag{11}$$

$$P_{E100} - P_{R6} = P_{E0} + \rho P_{RIN} \tag{12}$$

If biodiesel and petroleum-based diesel are both included in the diesel blend, then the blender cost of biodiesel and the blender cost of petroleum-based diesel must be equal.

Gasoline blenders have a third choice variable, the fraction of ethanol that is sugarcane ethanol. This term was omitted from the profit function above for simplicity. It results in the following condition relating the blender cost of corn ethanol to the blender cost of sugarcane ethanol. The price of cellulosic RINs is set equal to the price of advanced RINs plus 25 cents.

$$P_{E100} - P_{R6} = P^S_{E100} - P_{R5} \tag{13}$$

3.4 Market clearing conditions

The market-clearing condition for renewable RINs is that the generation of corn ethanol RINs, sugarcane ethanol RINs, and ethanol-equivalent biodiesel RINs equals RFS obligations. For each gallon of BOB or petroleum diesel, a refiner must submit RINs from all four RIN categories.

$$Q_{E100} + Q^S_{E100} + 1.5Q_{B100} = (Q_{E0} + Q_{B0})(\rho_3 + \rho_4 + \rho_5 + \rho_6) \tag{14}$$

$$Q^S_{E100} + 1.5Q_{B100} \geq (Q_{E0} + Q_{B0})(\rho_3 + \rho_4 + \rho_5) \tag{15}$$

$$1.5Q_{B100} \geq (Q_{E0} + Q_{B0})(\rho_4) \tag{16}$$

[19] Online appendix section B.2 includes the E85 and diesel blender quantity and fraction conditions, as well as a more precise statement of the blender's problem including the choice of sugarcane ethanol.

The volume of ethanol in gasoline ($Q_{E100} + Q^S_{E100}$) is equal to the volume of RINs generated by blending ethanol into gasoline. The lefthand side of equation 14 is thus the supply of RINs, including 1.5 ethanol-equivalent RINs per gallon of biodiesel. Current RFS obligations are the volume of nonrenewable fuel times the RIN obligation per gallon. Nonrenewable fuel is the sum of petroleum-based gasoline (Q_{E0}) and petroleum-based diesel (Q_{B0}). The market-clearing conditions for advanced RINs and biodiesel RINs are similar. These are inequality constraints because excess advanced RINs can be used to meet the renewable mandate.

When markets clear, the production volume of blending components will be equal to the volume used by blenders in blended fuel. The market clearing conditions for blending components—ethanol, blendstock for oxygenate blending, biodiesel, and petroleum diesel—are:

$$Q_{E100} + Q^S_{E100} = F_{E10}Q_{E10} + F_{E85}Q_{E85} \tag{17}$$

$$Q_{E0} = (1 - F_{E10})Q_{E10} + (1 - F_{E85})Q_{E85} \tag{18}$$

$$Q_{B100} = F_{BX}Q_{BX} \tag{19}$$

$$Q_{B0} = (1 - F_{BX})Q_{BX} \tag{20}$$

4 Testing and estimating price relationships

The model is designed for performing policy experiments with RFS minimum volumes, and it also makes predictions about the relationships among prices of RINs, blending components, and blended fuels. This section has two goals. One goal is to show that the predicted price relationships are observed in the data, as a method of supporting the empirical relevance of the model. The other goal is to inform the calibration of model parameters for taxes and transportation costs.

RIN prices—The model predicts a hierarchy of RIN prices: in descending order, biodiesel, advanced, renewable ($P_{R4} \geq P_{R5} \geq P_{R6}$). Figure 2 shows that this has been the case. For most of

2011 and 2012, there were large gaps between the three prices, and then in 2013 the prices converged. The model predicts that the prices will converge if excess biodiesel RINs are being used to satisfy the renewable mandate. RIN price changes should be attributed to changes in expectations, which I do not explicitly model.[20]

Price and blender cost of E10—The model predicts that the retail price of E10 will equal the blender cost (BC) of components.[21] For the empirical test, I include the cost to the blender of octane-boosting additives (OBA), which was omitted from the exposition of the model for simplicity. I assume that octane-boosting additives are added in proportion to BOB above 90% at a price equal to 15% of the price of BOB.[22]

Figure 3 shows that the retail price of E10 exceeds the blender cost of components. This makes sense because the retail price includes components that were not in the model like transportation costs and taxes. When I simulate the model, I add a wedge between the retail price and the blender cost. I allow the wedge to include an ad valorem component ν_{G1} and a per unit component ν_{G2} because some gasoline taxes are ad valorem and others are expressed per unit volume. Equation 11 becomes: $RP_{E10} = BC_{E10}\nu_{G1} + \nu_{G2}$. I estimate both components empirically, and use the estimates for calibrating the model.

The parameter ν_{G2} expresses a constant markup per gallon. To estimate the constant markup per gallon ν_{G2}, I regress the retail price of E10 on the blender cost of components.[23] Table 2 shows that the retail price exceeds the blender cost of components by about 72 cents.[24] I use this estimate for the parameter ν_{G2} in simulations.

[20] Lade, Lin, and Smith (2014) examine RIN prices in a dynamic context.

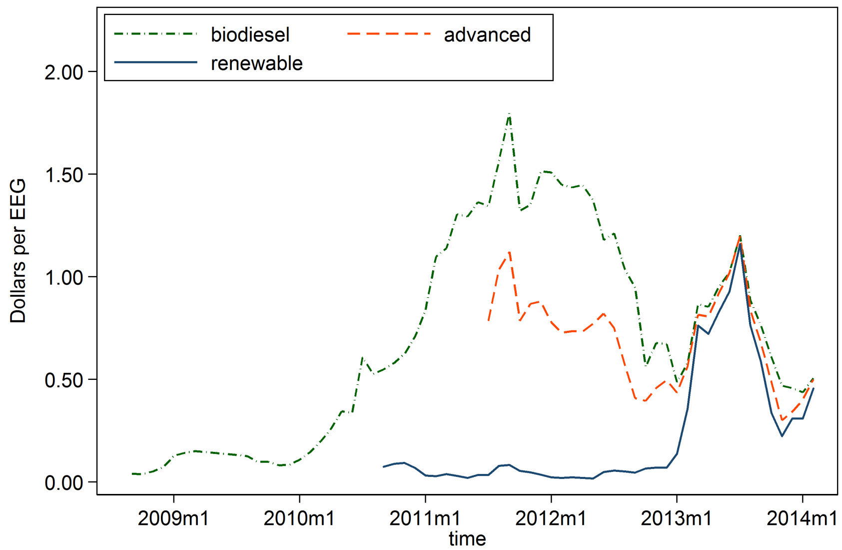
[21] $BC_{E10} = F_{E10}(P_{E100} - P_{R6}) + (1 - F_{E10})(P_{E0} + \rho P_{RIN}) + (.1 - F_{E10})(\nu_{OBA} P_{E0})$

[22] Babcock, Moreira, and Peng (2013) posit an ethanol demand curve which is elastic for low ethanol volumes at a price ratio relative to BOB of 1.2 ($\nu_{OBA} = 0.20$). As the ethanol volume approaches the blendwall in their demand curve, the price ratio decreases, so I assume a lower price ratio ($\nu_{OBA} = 0.15$).

[23] The equation is: $RP_{E10,t} = \nu_{G2} + \beta_1 BC_{E10,t} + u$.

[24] This is very close in concept and magnitude to the "wholesale-to-retail price markup" of 75 cents reported by Pouliot and Babcock (2014).

Figure 2: Monthly RIN prices



Note: This figure shows the monthly RIN prices calculated from Bloomberg. RIN prices are reported in separate vintages depending on the year in which the RIN was generated. A monthly average within vintage is calculated as a simple average of available daily prices. Missing months, which occur mostly in the earlier years of the mandate when RIN prices were near zero, are linearly interpolated. The price is then taken as the maximum among all reported vintages.

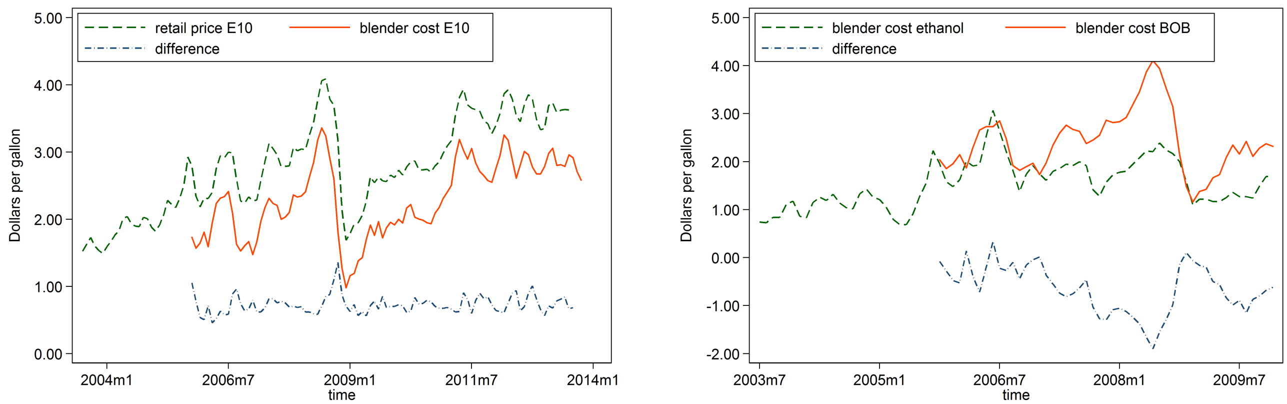
The parameter ν_{G1} expresses the passthrough of blender costs to the retail price of E10. In the model, arbitrage is instantaneous, but in data cost changes may not be passed through right away or at all. As a simple exercise, I regress retail price on a distributed lag of the blender cost. The regression will be endogenous if there is reverse causality from retail prices to blender costs. Table 3 shows the results of the regression.[25] A price change in the blender cost of components is followed by a price change in the retail price of E10. I use the three-month estimate that 109% of a change to the blender cost of components is reflected in the retail price for the parameter ν_{G1} in simulations. An effect larger than 100% is consistent with passing through ad valorem taxes.

Blending components of E10—The model predicts that the blender cost of ethanol will equal the blender cost of BOB whenever the blend fraction is interior, i.e. not at the 0% or 10% boundaries.[26] This relationship is expressed by equation 12. Figure 3 shows that this prediction fails—the

[25] The regression equation is $\Delta RP_{E10,t} = \beta_0 + \sum_{i=0}^{2} \beta_{i-1} \Delta\Delta BC_{E10,t-i} + \nu_{G1} \Delta BC_{E10,t-3} + u$. See Knittel, Meiselman, and Stock (2015) for a more thorough treatment of passthrough under the RFS.

[26] Salvo and Huse (2011) observe this link between the price of ethanol and the price of BOB in Brazil.

Figure 3: E10 retail price and blender cost



Note: The left panel compares the retail price of E10 with the blender cost of E10. The right panel compares the blender cost of ethanol to the blender cost of BOB. Retail price is the U.S. city average retail price of unleaded regular gasoline, from EIA. Blender cost (BC) is calculated according to the following equation: $BC_{E10} = F_{E10}(P_{E100} - P_{R6}) + (1 - F_{E10})(P_{E0} + \rho P_{RIN}) + (.1 - F_{E10})(\nu_{OBA} P_{E0})$. Ethanol fraction F_{E10} is ethanol share of finished gasoline consumption, from EIA. Ethanol price P_{E100} is blender cost of ethanol with credit, from U.S. Bioenergy Statistics. The vector of RIN prices P_{RIN} includes renewable P_{R6}, advanced P_{R5}, and biodiesel P_{R4} RIN prices, from Bloomberg. BOB price P_{E0} is generic RBOB gasoline (XB1), from Bloomberg. The vector of RFS fractions ρ is from past EPA rules. The cost of octane-boosting additives is assumed to be proportional to the price of BOB, $\nu_{OBA} = 0.15$

blender cost of ethanol is in general not equal to the blender cost of BOB. I attribute this to regional variation that is not captured by the model. Individual blenders in Minnesota face a blender cost of ethanol below the national average because of local subsidies and proximity to ethanol distilleries. Minnesota blenders are therefore more likely to be at the corner solution, blending in the maximum 10% ethanol into E10 gasoline, when blenders in other states like Mississippi still observe a cost of ethanol above the cost of BOB.[27] Even though the blender cost of ethanol is not equal to the blender cost of BOB nationally, the model can still be a good description of local choices.

Retail price and blender cost of diesel and E85—The model's predictions for diesel prices are supported by the data.[28] The predictions for diesel are parallel to the predictions for E10: retail

[27] Online Appendix Figure 12 illustrates regional variation in ethanol blending. States are shaded according to the fraction of ethanol in blended gasoline from 2003 to 2011. Minnesota, Illinois, and California stand out as having relatively high fractions, while Texas and the Southeast have relatively low fractions.

[28] Online Appendix Section C illustrates the price relationships for diesel and E85 and estimates a price wedge between the retail price and blender cost of diesel.

Table 2: Regression of retail price of E10 on blender cost of E10

$BC_{E10,t}$	1.006***
	(0.0252)
Constant	0.717***
	(0.0595)
Observations	95
R-squared	0.945

Standard errors in parentheses
*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

Note: This table reports regression results of retail price on blender cost of E10 using monthly data. See note on Figure 3.

price is equal to blender cost of components (with a stable wedge), and the blender cost of one component is equal to the blender cost of the other component at interior blends. For diesel, an "interior blend" corresponds to the situation in which both unblended petroleum-based diesel and a diesel blend with 5% biodiesel are being consumed.

The model's predictions for E85 prices are not supported by the data. This is not surprising because E85 volumes are low and E85 price data are less reliable than E10 and diesel price data. National prices for E85 are biased downward relative to the blender cost of components because they are weighted by sales volume, which is highest in regions of the country where the price is lowest. Furthermore, demand for E85 is not large enough to impose a relationship between the blender cost of ethanol and the blender cost of BOB. In simulations, I use the estimated E10 price wedges for all blends of gasoline.

5 Calibration

The calibration is designed to permit policy experiments for 2014. Table 7 shows the values used for model parameters, and I discuss the parameters using the table as a guide.

RFS fractions—The RFS renewable fraction is calibrated to the blendwall and the other RFS fractions to the 2014 Notice of Proposed Rulemaking (EPA, 2013). This is appropriate because the

Table 3: Regression of change in retail price of E10 on lagged changes in blender cost of E10

$\Delta\Delta BC_{E10,t}$	0.597***
	(0.0463)
$\Delta\Delta BC_{E10,t-1}$	1.079***
	(0.0530)
$\Delta\Delta BC_{E10,t-2}$	1.129***
	(0.0591)
$\Delta BC_{E10,t-3}$	1.093***
	(0.0656)
Constant	-0.000346
	(0.00873)
Observations	91
R-squared	0.851

Standard errors in parentheses
*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

Note: This table reports regression results of a change in retail price on a distributed lag of blender cost of E10 using monthly data. See note on Figure 3.

goal of the calibration is to perform policy experiments for 2014. In the policy experiment, I will increase the renewable RFS fraction and observe the equilibrium response as the RFS obligation exceeds the blendwall.

Demand elasticities and income—Values for demand elasticity parameters are based on estimates in the literature. Babcock, Barr, and Carriquiry (2010) construct several demand curves for nonfuel corn products. I use their estimated elasticity for corn feed -0.25. Hughes, Knittel, and Sperling (2008) estimate a range for gasoline demand elasticity in the 2000s of -0.034 to -0.077. However, Coglianese, Davis, Kilian, and Stock (2015) argue that gasoline demand elasticity estimates that use contemporary tax changes as an instrument are too low, and they offer a much higher point estimate of -0.368. In my base case I use a gasoline demand elasticity between these two estimates (-0.20), and the results are robust to alternative simulations with a lower elasticity (-0.03) and a higher elasticity (-0.37). I use a diesel demand elasticity of -0.07 from Dahl (2012).

Corn supply—Values for three corn supply parameters are from various sources. For corn supply elasticity ($\eta_C = 0.05$), I rely on Roberts and Schlenker (2013), who identify supply elasticities

Table 4: Calibrated parameters

Parameter	**Symbol**	**Value**	**Source/Target**
nonfuel corn demand elasticity	ϵ_C	-0.25	Babcock et al. (2010)
gasoline demand elasticity	ϵ_G	-0.20	Hughes et al. (2008) and Coglianese et al. (2015)
diesel demand elasticity	ϵ_B	-0.07	Dahl (2012)
corn supply elasticity	η_C	0.05	Roberts and Schlenker (2013)
bushels of corn per gallon of ethanol	μ	0.361	Westhoff (2006)
ethanol wedge over nonfuel corn	ν_C	0.76	average wedge 1982 to 2013
petrogas supply elasticity	η_G	10	assumption
petrodiesel supply elasticity	η_D	10	assumption
energy-equivalent e10 gallons per e85	γ	0.86	EPA BTU/barrel: 3.6 E100, 5.3 E0
gasoline price wedge per unit value	ν_{G1}	1.09	Section 4
gasoline price wedge per unit volume	ν_{G2}	0.72	Section 4
diesel price wedge per unit value	ν_{B1}	1.07	Section 4
diesel price wedge per unit volume	ν_{B2}	0.81	Section 4
gasoline demand elasticity of substition	$\frac{\sigma}{1-\sigma}$	-7.6	Salvo and Huse (2013)
gasoline demand share	α	0.65	0.3 bgals E85
sugarcane ethanol supply intercept	$log(\theta_S)$	1.23	280 mgals net imports
sugarcane ethanol supply elasticity	η_S	35.1	Babcock, Moreira, and Peng (2013)
biodiesel refining supply intercept	$log(\theta_B)$	0.43	1.28 bgals B100
biodiesel refining supply elasticity	η_B	1.37	Babcock, Moreira, and Peng (2013)
soy input cost per biodiesel gallon	ψ_B	3.6	price of soy oil

This table omits some parameters. Mandate fractions (ρ) are listed in table 1. The demand and supply intercepts at the calibrated point are in the online appendix.

of storable commodities with the express purpose of evaluating the RFS. For the bushels of corn input into one gallon of ethanol ($\mu = 0.361$), I use the ratio in a briefing from the Food and Agricultural Policy Research Institute (Westhoff, 2006). For the difference between the price of ethanol and the price of corn inputs into ethanol ($\nu_C = 0.76$), I use the average of the observed difference from 1982 through 2013.[29]

Petroleum-based blending components—I assume a supply elasticity for BOB and diesel. The market for these products is sufficiently global that small changes in the United States are

[29] The price of ethanol reflects the cost of the corn input, the cost of the refining process, and the revenue from distillers grains, a valuable byproduct of ethanol production.

unlikely to have a large impact on the global price. If a refiner can sell BOB outside the United States at some global price without paying the cost of RFS compliance, then the price the refiner receives in the United States must exceed the global price by the cost of RFS compliance. So $P_{\text{US}} = P_{\text{WORLD}} + \text{RFS COST}$. In my base case I use an elasticity of 10, and the results are robust to alternative choices of 5 or 20.

Energy-equivalence factor—The E10-E85 energy-equivalence factor is computed using EPA assumptions about the energy content of ethanol and BOB. In the 2014 proposal, the EPA assumes 3.561 million British thermal units (BTU) per barrel for ethanol and 5.253 million BTU per barrel for BOB. I assume the fraction of ethanol in E10 is 10% and the ethanol fraction in E85 is 51%, and I use an energy-equivalence factor of 0.86 in my base case. The results are robust to assuming the ethanol fraction in E85 is 85%, which implies an energy-equivalence factor of 0.75.

Blended fuel price wedge and regional variation—Section 4 describes estimation of price wedges for gasoline and diesel. The gasoline markup per gallon is 72 cents, and the gasoline passthrough of blender costs is 1.09. The diesel markup per gallon is 81 cents, and the diesel passthrough of blender costs is 1.07.

The model does not make regional distinctions even though there is substantial regional variation.[30] There are state-specific taxes and subsidies on biofuel, gasoline and diesel. The cost of transporting ethanol distilled in Minnesota to Wisconsin is considerably different than the cost of transporting it to Alabama. The aggregate price relationship between blender cost and retail price is likely to be noisier than the model predicts due to regional variation. The main regional-related shortcoming of the model is the need to choose a single national blender cost of ethanol. Ethanol transportation costs vary widely by region. Variation in the price of BOB is likely to be less severe

[30] Pouliot and Babcock (2014) also do not distinguish among regions, and their wholesale-retail price wedge is 75 cents. That is similar to my estimate of 72 cents. Liu and Greene (2013) compute region-specific E85 demand intercepts to account for such differences.

because it is often transported through low-cost pipelines.

E85 demand—The elasticity of substitution between E10 and E85 is inferred from the behavior of drivers switching between ethanol and gasoline. For tractability, I assume a constant elasticity of substitution. Salvo and Huse (2013) find that 20% of Brazilian FFV drivers choose ethanol even when it is 20% more expensive per mile, and 20% of FFV drivers choose gasoline even when ethanol is 20% less expensive per mile. From these points, I calculate an elasticity of -7.6. I also solve the model with a higher elasticity and a lower elasticity. For each elasticity, the E10 demand share α is calculated such that the E85 demand curve passes through 300 million gallons at a price of \$3.50.[31]

There are two significant differences between what Salvo and Huse measure and what I model. First, they measure the elasticity of substitution between 100% ethanol and 100% petroleum gasoline, whereas the relevant elasticity in my model is between E85 and E10. This difference in fuel blends should lead their estimate to understate the elasticity in my model because whatever non-performance factors consumers take into account are reduced for less extreme blends. Second, they measure the elasticity for FFV drivers only, whereas my model has a representative consumer, and FFVs are only about 5% of the fleet. This difference in fleet composition should lead their estimate to overstate the elasticity in my model, although drivers may convert their non-flex fuel vehicles to become FFVs.

Biofuel supply—I assume biofuel supply elasticities based on discussion by Babcock, Moreira, and Peng (2013). They argue that the supply of sugarcane ethanol from Brazil should be very elastic because Brazil's flexible infrastructure—FFVs and fueling stations—facilitates substitution between ethanol and gasoline.[32] I use a sugarcane ethanol supply elasticity of 35 in the baseline calibration. I choose the sugarcane ethanol supply intercept such that consumption will be equal to 280 million gallons at the calibrated point. I use a biodiesel supply elasticity of 1.37 in the baseline calibration.[33]

[31] See Online Appendix D for a comparison to E85 demand estimated by Pouliot and Babcock (2014)

[32] Figure 15 in Babcock, Moreira, and Peng (2013) illustrates a supply curve that passes through 0 volume at a price of \$2.70 and 1.8 billion gallons at a price of \$3.10. In my model, this corresponds to a supply elasticity of about 35.

[33] This elasticity is based on Babcock, Moreira, and Peng (2013), who estimate that the quantity supplied of biodiesel is 1.28 billion gallons when price exceeds variable cost by 43 cents per gallon and 1.85 billion gallons when price exceeds

I choose the supply intercept such that biodiesel production will be equal to 1.28 billion gallons at the calibrated point. The results are robust to alternate sugarcane ethanol supply elasticities and to alternate biodiesel supply elasticities.

Supply and demand intercepts—The model has 26 equations and 26 endogenous variables. All but six of the parameters are discussed above. The remaining six parameters are the demand intercepts for nonfuel corn, gasoline, and diesel, and the supply intercepts for corn, BOB, and petrodiesel. Six endogenous variables are chosen based on projections or recent history, and the model is solved as if the six unknown parameters were endogenous variables.

I set the quantity of BOB and petrodiesel to the quantities assumed in the 2014 proposal, 119.5 bgals and 45.7 bgals. I set the quantity of nonfuel corn to 6 billion bushels and the price of petrodiesel to \$3.00, in line with their recent observed values. At the blendwall, the model requires the blender cost of ethanol to equal the blender cost of BOB. In order to calibrate the model at the blendwall, price of BOB must be below the price of ethanol, so I set the price of BOB to \$2.50 and the price of ethanol to \$3.00.

Because six "endogenous variables" are chosen and six "parameters" are permitted to take on any value, the model still describes a system with 26 equations and 26 unknowns. I solve the system and retain the parameter values for the demand and supply intercepts for use in simulation. For robustness checks using alternative elasticities, I recalibrate these six intercepts.

5.1 Empirical verification

The model is a good description of the market for renewable fuels because, at the calibrated point, endogenous variables are near their observed values in 2012 and 2013. Table 5 lists the endogenous variables in the model, their observed values in 2012 and 2013, and their calibrated values. For

variable cost by one dollar.

Table 5: Empirical verification of endogenous variables

Variable	Actual 2012	Actual 2013	Calibration	Unit	Description
F_{BX}	1.7%	2.4%	2.7%	%	fraction of biodiesel in diesel
F_{E10}	9.7%	9.9%	9.9%	%	fraction of ethanol in E10 gasoline
F_{E85}	71%	71%	51%	%	fraction of ethanol in E85 gasoline
P_{BX}	3.95	3.94	4.04	usd/gal	price of diesel
P_{E10}	3.69	3.62	3.51	usd/gal	price of E10 gasoline
P_{E85}	3.33	3.23	3.67	usd/gal	price of E85 gasoline
Q_{BX}	53.0	54.5	47.0	bgal	quantity of diesel
Q_{E10}	133.7	133.2	132.5	bgal	quantity of E10 gasoline
Q_{E85}	0.2	0.2	0.3	bgal	quantity of E85 gasoline
P_{B0}	3.11	3.02	3.00	usd/gal	price of petroleum-based diesel
P_{B100}	4.51	4.76	4.44	usd/gal	price of biodiesel
P_{E0}	3.03	2.97	2.50	usd/gal	price of BOB
P_{E100}	2.58	2.40	3.00	usd/gal	price of corn ethanol
Q_{B0}	52.1	53.2	45.7	bgal	quantity of petroleum-based diesel
Q_{B100}	0.9	1.3	1.3	bgal	quantity of biodiesel
Q_{E0}	121.2	120.7	119.5	bgal	quantity of BOB
Q_{E100}	12.7	12.7	13.0	bgal	quantity of ethanol
Q^S_{E100}	0.32	0.20	0.28	bgal	quantity of sugarcane ethanol
P_C	6.67	6.47	6.21	usd/bsh	price of nonfuel corn
Q_C	7.6	6.9	7.0	bbsh	quantity of nonfuel corn
P_{R3}	0.89	0.95	1.05	usd/gal	price of cellulosic RINs
P_{R4}	1.12	0.76	0.95	usd/gal	price of biodiesel RINs
P_{R5}	0.64	0.70	0.41	usd/gal	price of advanced RINs
P_{R6}	0.04	0.59	0.10	usd/gal	price of renewable RINs

Note: Quantities in the model are expressed in billions of dollars, gallons, or bushels. Prices are expressed in dollars per gallon or bushel. Calibrated values for six variables ($P_{B0}, P_{E0}, P_{E100}, Q_{B0}, Q_{E0}, Q_C$) are chosen; the remaining values and six demand and supply intercepts are solved using the model system of equations.

calibrating price of renewable RINs at the blendwall, 2012 is more informative. For most other variables, 2013 is more informative.

The discrepancy between calibrated and actual diesel volume comes from the EPA's 2014 proposal, which reports a projected diesel volume of 47 billion gallons. I do not know why this projection is so low. However, I defer to the EPA on this point. The effect of this deference is that the blended diesel demand intercept is lower than it would otherwise be. The results are robust to alternative assumptions about the blended diesel demand intercept.

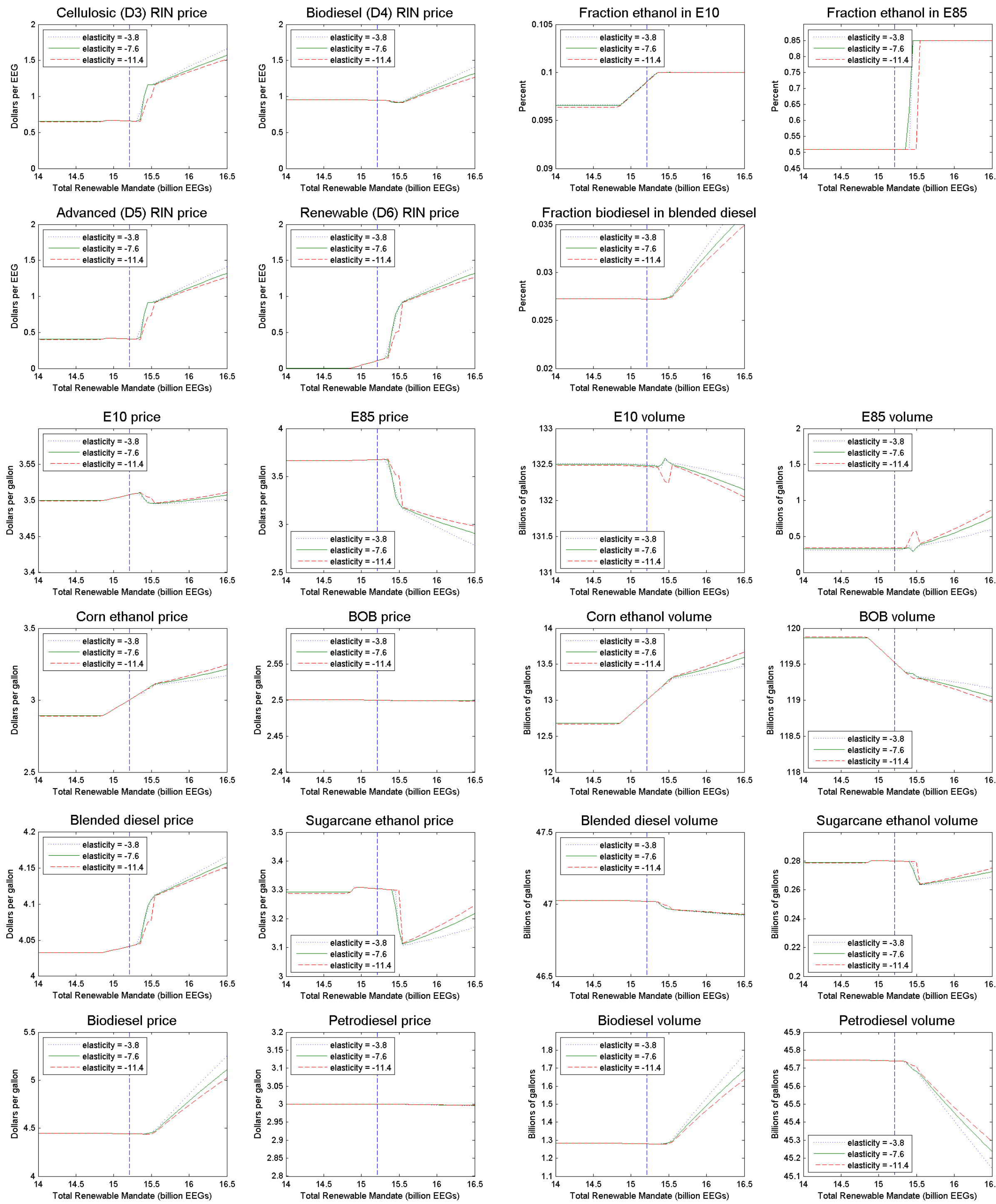
I attribute deviations in the fraction of ethanol in E85 gasoline and the price of E85 to regional variation. Real gasoline blenders have costs that differ by region. In the model, there is just an average national cost, so the calibrated fraction of ethanol in E85 is more likely to be exactly 51% or exactly 85%. E85 prices are more likely to be reported in regions with lower E85 prices.

6 Results

I simulate policy alternatives by solving the system of equations numerically for a range of possible values for the renewable fuel mandate. This is represented by the parameter ρ_6 in the model, which I vary exogenously. A key parameter in the model is the elasticity of substitution between E10 and E85, so I report results for the base case, a higher alternative and a lower alternative. Figure 4 shows simulation results for many endogenous variables. In each graph, the horizontal axis is the total RFS volume obligation for all four RIN categories combined, expressed in ethanol-equivalent gallons. The RFS fractions for cellulosic, biodiesel, and advanced are held constant, so the only change is in the renewable fraction. The dashed vertical line in each graph is the blendwall.

These results tell a story of how the market responds to increasing the RFS in light of the blendwall and the linkage among RIN prices. When the RFS is at the blendwall, the fraction of ethanol in E10 is below 10% and the fraction in E85 is above 10%. The first response of the market is to increase the fraction of ethanol in E10 to the 10% limit. When this is no longer possible, the price of renewable RINs increases rapidly until the blender cost of ethanol reaches the blender cost of BOB. At that point blenders are indifferent between adding BOB and ethanol to E85, and the blend fraction in E85 increases from 51% to 85%. When the maximum E85 blend is reached, the price of renewable RINs continues increasing, which is passed through to consumers in the form of a lower

Figure 4: Simulation for three values of gasoline demand elasticity of substition



Note: These graphs depict the results of numerically solving the system of equations for many values for the renewable fuel mandate (14 to 16.5 billion ethanol equivalent gallons) and three values for the gasoline demand elasticity of substitution (-3.8, -7.6, -11.4).

price of E85. Consumers shift from E10 toward E85 until the price of renewable RINs reaches the price of biodiesel RINs. From then on, both biodiesel production and E85 consumption rise.

The price of blended diesel responds to the mandate even though the price of E10 does not. This is because the blended fuels respond differently to a change in the price of renewable RINs. As the price of renewable RINs rises, the blender cost of petrodiesel and the blender cost of BOB rise by the same amount. The cost of BOB is offset by a decline in the blender cost of ethanol, but the blender cost of biodiesel is unchanged.

6.1 Welfare analysis

I estimate the welfare effects of an increase in the RFS volume by calculating the change in emissions, the change in producer and consumer surplus, and cost per ton of emissions reduction. I compare the cost per ton of emissions reduction to the social cost of carbon.

I choose measures of life cycle emissions that are likely to be seen as most relevant by the EPA.[34] I assume CO_2 emissions for petroleum-based gasoline and diesel are 16.8 and 15.8 kilograms per million British thermal units of energy.[35] I assume blending components have the following energy content: 0.124 million British thermal units per gallon of petroleum gasoline, 0.137 mmbtu/gal of petroleum diesel, 0.128 mmbtu/gal of biodiesel, and 0.085 mmbtu/gal of ethanol.[36] I assume the following emissions reductions per unit energy relative to the petroleum baseline: a 52% reduction for biodiesel, 19% for corn ethanol, and 78% for sugarcane ethanol.[37] These assumptions imply life cycle carbon emissions are 2.09, 2.17, 0.97, 0.31, and 1.15 kg/gal for BOB, petrodiesel, biodiesel, sugarcane ethanol, and corn ethanol. To calculate total emissions, I multiply the consumption volume of each blending component by its life cycle emissions.

Figure 5 shows that increasing the mandate from 15 to 16 billion EEGs reduces emissions by

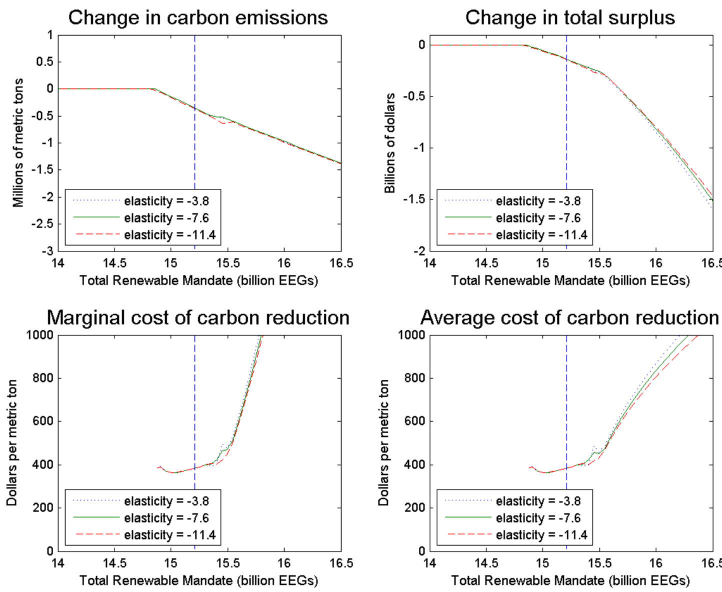
[34] There is not a consensus on these life cycle emissions measures. Some analysts have claimed that the life cycle emissions from corn ethanol actually exceed life cycle emissions from petroleum-based gasoline. I use estimates from the Department of Energy and the EPA because they are most likely to be used in evaluating policy alternatives.

[35] Regulatory Impact Analysis, Environmental Protection Agency, EPA-420-R-10-006, February 2010, page 467.

[36] The energy content is the higher heating value reported in Alternative Fuels Data Center (2013a), which is consistent with values reported in the 2014 RFS proposal.

[37] Biodiesel reduction is from Alternative Fuels Data Center (2014a) and ethanol reductions are from Alternative Fuels Data Center (2014b).

Figure 5: Emissions and welfare



Note: Total emissions equal consumption volume times life cycle emissions, by blending component.

about 1 million metric ton. Around the blendwall, the marginal renewable volume is corn ethanol, which is only a small reduction in emissions relative to BOB. Emissions decline mostly through the channel of substituting ethanol for BOB until the price of renewable RINs rises enough to meet the price of biodiesel RINs. Biodiesel is a larger reduction in emissions relative to petroleum diesel, but the RFS generates 1.5 ethanol-equivalent RINs for each gallon of biodiesel. When marginal increases in the mandate are also met by biodiesel, the pace of emissions changes but not by much.

Increasing the mandate from 15 to 16 billion EEGs reduces total surplus by about $800 million. Consumer surplus declines are offset by an increase in producer surplus. Producer surplus increases because the price of corn and the price of biodiesel rise, so there is a larger return to inframarginal production. The change in consumer surplus and producer surplus does not include private valuation of environmental quality. Total surplus declines at a slower pace once adjustment to the mandate is achieved through both biodiesel and ethanol. Marginal cost of reducing carbon emissions rises as the RFS volume increases. I find that the average cost of reducing carbon emissions by increasing the mandate from 15 to 16 billion gallons is about $800 per metric ton. This is much larger than the social cost of carbon used by policymakers.[38]

7 Conclusion

This paper shows that the cost of reducing carbon emissions using the RFS is high in the short run. The cost of shifting behavior is relatively high because the blendwall limits the extent to which the mandate can be met through regular gasoline. The cost of shifting behavior is mitigated by the linkage among the different categories of renewable fuel; the renewable mandate can be met by shifting consumption from E10 to E85 and also shifting the blend composition of diesel towards biodiesel. The benefit of shifting consumption from E10 to E85 is relatively low because the life cycle carbon emissions of conventional ethanol are nearly as high as the life cycle carbon emissions of petroleum-based gasoline. The benefit of shifting the blend composition of diesel towards biodiesel is more substantial, but biodiesel is expensive to produce.

In the long run, the RFS could still be beneficial. The Renewable Fuel Standard was built to support investment in production technology for cellulosic fuel, which emits around one fifth as much greenhouse gas as petroleum-based gasoline for the same energy output. The RFS pushes refiners to develop technology, blenders to invest in infrastructure, and consumers to drive FFVs. Whether those investments are worthwhile is beyond the scope of this analysis, as are the long term costs of devoting more agricultural land to corn production and integrating the supply of food with the supply of fuel. Policymakers should consider both the short run and the long run tradeoffs.

References

Alternative Fuels Data Center. Fuel properties comparison, 2013a. URL `http://www.afdc.energy.gov/fuels/fuel_comparison_chart.pdf`. (accessed 4/10/2014).

Alternative Fuels Data Center. Handbook for handling, storing, and dispensing e85 and other ethanol-gasoline blends, 2013b. URL `http://www.afdc.energy.gov/uploads/publication/ethanol_handbook.pdf`. (accessed 4/8/2015).

[38] The social cost of carbon for 2014 is estimated to be $36. See Interagency Working Group on Social Cost of Carbon (2013).

Alternative Fuels Data Center. Biodiesel vehicle emissions, 2014a. URL `http://www.afdc.energy.gov/vehicles/diesels_emissions.html`. (accessed 4/10/2014).

Alternative Fuels Data Center. Ethanol vehicle emissions, 2014b. URL `http://www.afdc.energy.gov/vehicles/flexible_fuel_emissions.html`. (accessed 4/10/2014).

Soren T Anderson. The demand for ethanol as a gasoline substitute. *Journal of Environmental Economics and Management*, 63(2):151–168, 2012.

Soren T Anderson and Andrew Elzinga. A ban on one is a boon for the other: strict gasoline content rules and implicit ethanol blending mandates. *Journal of Environmental Economics and Management*, 67(3):258–273, 2014.

Bruce A Babcock. Rfs compliance costs and incentives to invest in ethanol infrastructure. *CARD Policy Brief*, 2013.

Bruce Alan Babcock, Kanlaya Jintanakul Barr, and Miguel Alberto Carriquiry. Costs and benefits to taxpayers, consumers, and producers from us ethanol policies. 2010.

Bruce Alan Babcock, Marcelo Moreira, and Yixing Peng. Biofuel taxes, subsidies, and mandates: Impacts on us and brazilian markets. 2013.

Xiaoguang Chen, Haixiao Huang, Madhu Khanna, and Hayri Önal. Alternative transportation fuel standards: Welfare effects and climate benefits. *Journal of Environmental Economics and Management*, 67(3):241–257, 2014.

John Coglianese, Lucas W Davis, Lutz Kilian, and James H Stock. Anticipation, tax avoidance, and the price elasticity of gasoline demand. 2015.

Jingbo Cui, Harvey Lapan, GianCarlo Moschini, and Joseph Cooper. Welfare impacts of alternative biofuel and energy policies. *American Journal of Agricultural Economics*, page aar053, 2011.

Carol A Dahl. Measuring global gasoline and diesel price and income elasticities. *Energy Policy*, 41: 2–13, 2012.

Harry De Gorter and David R Just. The economics of a blend mandate for biofuels. *American Journal of Agricultural Economics*, 91(3):738–750, 2009.

Xiaodong Du and Miguel A Carriquiry. Flex-fuel vehicle adoption and dynamics of ethanol prices: lessons from brazil. *Energy Policy*, 59:507–512, 2013.

Xiaodong Du and Shanjun Li. Flexible-fuel vehicle adoption and the us biofuel market. *Available at SSRN 2583808*, 2015.

EPA. 2014 standards for the renewable fuel standard program; proposed rule. 78(239):40 CFR Part 80, 2013.

Stephen P Holland, Jonathan E Hughes, Christopher R Knittel, and Nathan C Parker. Unintended consequences of transportation carbon policies: Land-use, emissions, and innovation. *National Bureau of Economic Research*, 2013.

Jonathan E Hughes, Christopher R Knittel, and Daniel Sperling. Evidence of a shift in the short-run price elasticity of gasoline demand. *The Energy Journal*, 29(1):113–134, 2008.

Interagency Working Group on Social Cost of Carbon. Technical update of the social cost of carbon for regulatory impact analysis. Technical report, United States Government, 2013.

Christopher R Knittel, Ben S Meiselman, and James H Stock. The pass-through of rin prices to wholesale and retail fuels under the renewable fuel standard. 2015.

Gabriel E Lade, C-Y Cynthia Lin, and Aaron Smith. Policy shocks and market-based regulations: Evidence from the renewable fuel standard. 2014.

Gabriel E Lade, C-Y Cynthia Lin, and Aaron Smith. Ex-post costs and rin prices under the renewable fuel standard. 2015.

Harvey Lapan and GianCarlo Moschini. Second-best biofuel policies and the welfare effects of quantity mandates and subsidies. *Journal of Environmental Economics and Management*, 63(2):224–241, 2012.

Changzheng Liu and David L Greene. Modeling the demand for e85 in the united states. 2013.

Matthew S Luchansky and James Monks. Supply and demand elasticities in the us ethanol fuel market. *Energy Economics*, 31(3):403–410, 2009.

Lihong Lu McPhail and Bruce A Babcock. Impact of us biofuel policy on us corn and gasoline price variability. *Energy*, 37(1):505–513, 2012.

Sébastien Pouliot and Bruce A Babcock. The demand for e85: Geographical location and retail capacity constraints. *Energy Economics*, 45:134–143, 2014.

Cheng Qiu, Gregory Colson, and Michael Wetzstein. An ethanol blend wall shift is prone to increase petroleum gasoline demand. *Energy Economics*, 44:160–165, 2014.

Renewable Fuels Association. E15 stations, city and state. 2014. URL `http://www.ethanolrfa.org/pages/E15`.

Michael J Roberts and Wolfram Schlenker. Identifying supply and demand elasticities of agricultural commodities: Implications for the us ethanol mandate. *American Economic Review*, 103(6):2265–95, 2013.

Alberto Salvo and Cristian Huse. Is arbitrage tying the price of ethanol to that of gasoline? evidence from the uptake of flexible-fuel technology. *Energy Journal*, 32(3):119–148, 2011.

Alberto Salvo and Cristian Huse. Build it, but will they come? evidence from consumer choice between gasoline and sugarcane ethanol. *Journal of Environmental Economics and Management*, 66(2):251–279, 2013.

Randy Schnepf and Brent D Yacobucci. Renewable fuel standard (rfs): overview and issues. *Congressional Research Service: Washington, DC*, 2013.

Patrick C Westhoff. Fapri ethanol briefing materials for congressman peterson. 2006.

JunJie Wu and Christian Langpap. The price and welfare effects of biofuel mandates and subsidies. *Environmental and Resource Economics*, pages 1–23, 2014.

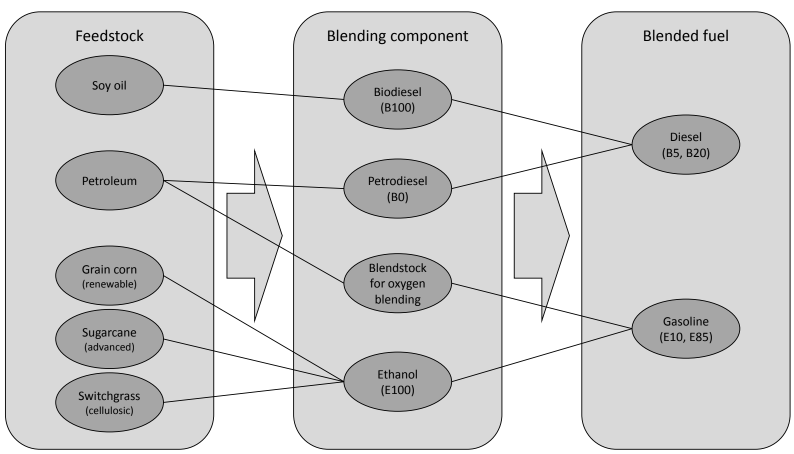
A Online Institutional Context Appendix [Not for publication]

Table 6: Transportation fuel volume, billions of gallons

Year	Gasoline bgals	Ethanol bgals	Ethanol/ Gasoline	Diesel bgals	Biodiesel bgals	Biodiesel/ Diesel
2005	140.4	4.1	2.9%	54.6	0.1	0.2%
2006	141.8	5.5	3.9%	56.7	0.2	0.4%
2007	142.4	6.9	4.8%	56.7	0.5	0.9%
2008	138.2	9.7	7.0%	53.8	0.7	1.3%
2009	138.0	11.0	8.0%	49.4	0.5	1.1%
2010	137.8	12.9	9.3%	52.6	0.3	0.6%
2011	134.1	12.9	9.6%	54.3	0.9	1.6%
2012	133.4	12.9	9.7%	53.2	0.9	1.7%
2013	133.8	13.2	9.9%	54.0	1.3	2.4%

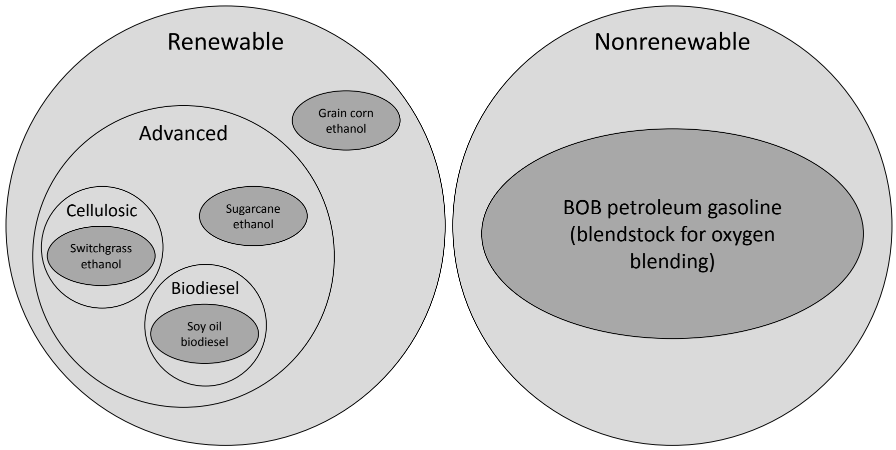
Note: By 2013, the ethanol fraction rose to the 10% limit in E10 gasoline. The biodiesel fraction was substantially below the 5% limit in B5 diesel. Short Term Energy Outlook.

Figure 6: Flow of fuel and feedstocks



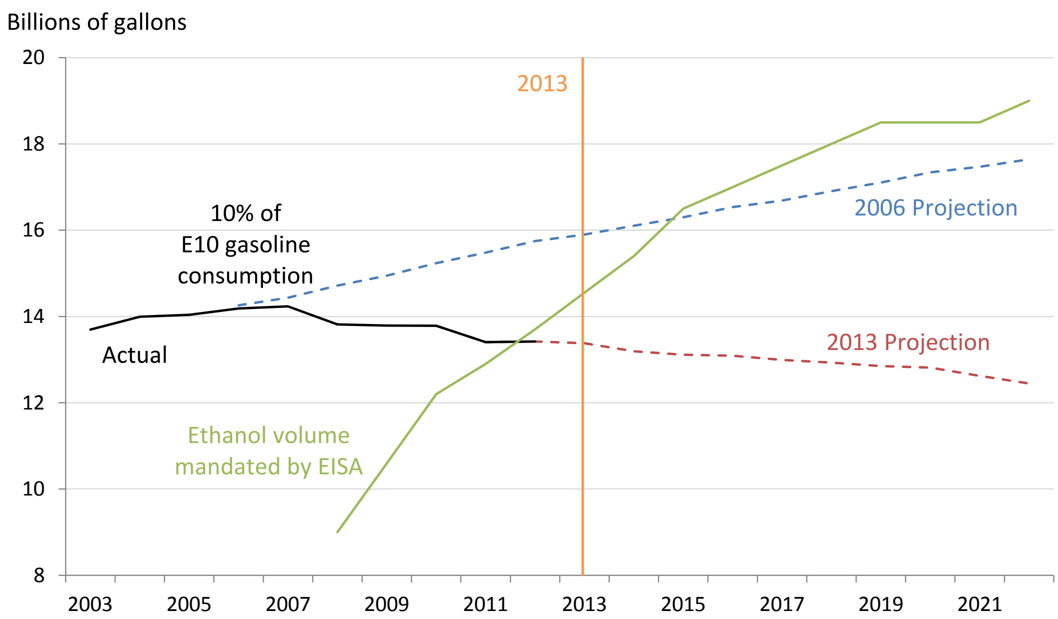
Note: The treatment of a gallon of ethanol under the RFS depends on the feedstock used to produce that gallon even though the performance of ethanol as a fuel does not depend on the feedstock.

Figure 7: Fuels for blending



Note: Light circles are sets. Dark ovals are the most common elements. The eligibility requirements for cellulosic fuel are more stringent than the eligibility requirements for advanced fuel; all fuel that qualifies as cellulosic also contributes to meeting the advanced requirement. Cellulosic and biodiesel are mutually exclusive subsets of advanced, and advanced is a subset of renewable.

Figure 8: The blendwall



Source: AEO 2006, AEO 2013, Energy Independence and Security Act of 2007.
Note: Ethanol volume is calculated as total renewable minus biomass-based diesel and cellulosic.

Table 7: Calibrated parameters

Parameter	**Symbol**	**Value**	**Source/Target**
mandate fraction for D3 RINs	ρ_3	0.0001	NPRM 2014
mandate fraction for D4 RINs	ρ_4	0.0116	NPRM 2014
mandate fraction for D5 RINs	ρ_5	0.0016	NPRM 2014
mandate fraction for D6 RINs	ρ_6	0.0787	blendwall
nonfuel corn demand elasticity	ϵ_C	-0.25	Babcock et al. (2010)
gasoline demand elasticity	ϵ_G	-0.20	Hughes et al. (2008) and Coglianese et al. (2015)
diesel demand elasticity	ϵ_B	-0.07	Dahl (2012)
corn supply elasticity	η_C	0.05	Roberts and Schlenker (2013)
bushels of corn per gallon of ethanol	μ	0.361	Westhoff (2006)
ethanol wedge over nonfuel corn	ν_C	0.76	average wedge 1982 to 2013
petrogas supply elasticity	η_G	10	assumption
petrodiesel supply elasticity	η_D	10	assumption
energy-equivalent e10 gallons per e85	γ	0.86	EPA BTU/barrel: 3.6 E100, 5.3 E0
income	Y	17000	GDP
gasoline price wedge per unit value	ν_{G1}	1.09	Section 4
gasoline price wedge per unit volume	ν_{G2}	0.72	Section 4
diesel price wedge per unit value	ν_{B1}	1.07	Section 4
diesel price wedge per unit volume	ν_{B2}	0.81	Section 4
gasoline demand elasticity of substition	$\frac{\sigma}{1-\sigma}$	-7.6	Salvo and Huse (2013)
gasoline demand share	α	0.65	0.3 bgals E85
sugarcane ethanol supply intercept	$log(\theta_S)$	1.23	280 mgals net imports
sugarcane ethanol supply elasticity	η_S	35.1	Babcock, Moreira, and Peng (2013)
biodiesel refining supply intercept	$log(\theta_B)$	0.43	1.28 bgals B100
biodiesel refining supply elasticity	η_B	1.37	Babcock, Moreira, and Peng (2013)
soy input cost per biodiesel gallon	ψ_B	3.6	price of soy oil
nonfuel corn demand intercept	$log(\phi_C)$	37.8	calibration
gasoline demand intercept	$log(\phi_G)$	224.5	calibration
diesel demand intercept	$log(\phi_B)$	193.9	calibration
corn supply intercept	$log(\theta_C)$	-45.4	calibration
BOB supply intercept	$log(\theta_G)$	0.21	calibration
petrodiesel supply intercept	$log(\theta_D)$	0.72	calibration

B Online Model Equations Appendix [Not for publication]

This appendix includes the full set of equations in the single-period model described in section 3. For the list of variables see Table 5. For the list of parameters see Table 7.

B.1 Consumers

The consumer's maximization problem:

$$\max_{Q_{E10},Q_{E85},Q_{BX},Q_C,Q_Z} \quad \phi_G \frac{\left[(\alpha)(Q_{E10})^{\frac{1}{\sigma}} + (1-\alpha)(\gamma Q_{E85})^{\frac{1}{\sigma}}\right]^{(\sigma)(1-\frac{1}{\epsilon G})}}{1-\frac{1}{\epsilon G}} + \phi_B \frac{Q_{BX}^{1-\frac{1}{\epsilon B}}}{1-\frac{1}{\epsilon B}} + \phi_C \frac{Q_C^{1-\frac{1}{\epsilon C}}}{1-\frac{1}{\epsilon C}} + Q_Z$$

The consumer's budget constraint:

$$P_{E10}Q_{E10} + P_{E85}Q_{E85} + P_{BX}Q_{BX} + P_C Q_C + Q_Z = Y \tag{B.1}$$

The first order conditions yield the following equations:

$$P_{E10} = \phi_G[(\alpha)(Q_{E10})^{\frac{1}{\sigma}} + (1-\alpha)(\gamma Q_{E85})^{\frac{1}{\sigma}}]^{\sigma-\frac{\sigma}{\epsilon G}-1} Q_{E10}^{(\frac{1-\sigma}{\sigma})}(\alpha) \tag{B.2}$$

$$P_{E85} = \phi_G[(\alpha)(Q_{E10})^{\frac{1}{\sigma}} + (1-\alpha)(\gamma Q_{E85})^{\frac{1}{\sigma}}]^{\sigma-\frac{\sigma}{\epsilon G}-1} Q_{E85}^{(\frac{1-\sigma}{\sigma})}(1-\alpha)\gamma \tag{B.3}$$

$$P_{BX} = \phi_B Q_{BX}^{-\frac{1}{\epsilon B}} \tag{B.4}$$

$$P_C = \phi_C Q_C^{-\frac{1}{\epsilon C}} \tag{B.5}$$

Combining equations (B.2) and (B.3) yields a more convenient equation relating E10 and E85 demand.

$$\frac{P_{E85}}{\gamma P_{E10}} = (\frac{Q_{E10}}{\gamma Q_{E85}})^{1-\frac{1}{\sigma}}(\frac{1}{\alpha}-1) \tag{A.3*}$$

I assume the fraction of ethanol in E10 is 10% for the purpose of calculating its energy content. The energy-equivalence factor γ expresses the number of gallons of E10 that have the same amount of energy as one gallon of E85. γ is a function of the fraction of ethanol in E85 F_{E85}.

$$\begin{aligned}
\gamma &= \frac{\text{gallons of E10}}{\text{gallon of E85}} \\
&= \frac{\text{BTU per gallon of E85}}{\text{BTU per gallon of E10}} \\
&= \frac{BTU_{E0} + F_{E85}(BTU_{E100} - BTU_{E0})}{BTU_{E0} + F_{E10}(BTU_{E100} - BTU_{E0})} \\
&= \frac{5.253 + F_{E85}(3.561 - 5.253)}{5.253 + 0.1(3.561 - 5.253)} \\
&= 1.03 - .33F_{E85}
\end{aligned}$$

The fraction of ethanol in E85 ranges from 51% to 85%, and the energy-equivalence factor ranges from 0.86 to 0.75.

B.2 Blenders

Define the vectors ρ and P_{RIN} such that they succinctly express the RFS compliance cost for one gallon of nonrenewable fuel:

$$\rho P_{RIN} = \rho_3 P_{R3} + \rho_4 P_{R4} + \rho_5 P_{R5} + \rho_6 P_{R6}$$

B.2.1 Gasoline Blenders

For simplicity, the role of sugarcane ethanol was omitted from the main text. The relationship among blender costs follows the same logic as for ethanol and BOB; the blender cost of corn ethanol must equal the blender cost of sugarcane ethanol. The E10 blender's maximization problem:

$$\begin{aligned}
\max_{Q_{E10},F_{E10},F^S_{E100}} \quad & Q_{E10}\Big(\Big[P_{E10} - F_{E10}\big[(1-F^S_{E100})(P_{E100}-P_{R6}) + F^S_{E100}(P^S_{E100}-P_{R5})\big] \\
& - (1-F_{E10})(P_{E0}+\rho P_{RIN}) - (.1-F_{E10})(\nu_{OBA}P_{E0})\Big]\nu_{G1}+\nu_{G2}\Big) \\
s.t. \quad & 0 \leq F_{E10} \leq 0.1
\end{aligned}$$

The E10 blender's first order conditions:

$$\begin{aligned}
P_{E10} =& \big[F_{E10}(P_{E100}-P_{R6}) + (1-F_{E10})(P_{E0}+\rho P_{RIN}) \\
& + (.1-F_{E10})(\nu_{OBA}P_{E0})\big]\nu_{G1}+\nu_{G2}
\end{aligned} \tag{B.6}$$

$$P_{E100}-P_{R6} = (1+\nu_{OBA})P_{E0}+\rho P_{RIN} \quad \text{or} \quad F_{E10}=0 \quad \text{or} \quad F_{E10}=.1 \tag{B.7}$$

$$P^S_{E100}-P_{R5} = P_{E100}-P_{R6} \quad \text{or} \quad F^S_{E100}=0 \quad \text{or} \quad F^S_{E100}=1 \tag{B.8}$$

The E85 blender's maximization problem:

$$\begin{aligned}
\max_{Q_{E85},F_{E85}} \quad & Q_{E85}\Big(\big[P_{E85} - F_{E85}(P_{E100}-P_{R6}) \\
& - (1-F_{E85})(P_{E0}+\rho P_{RIN})\big]\nu_{G1}+\nu_{G2}\Big) \\
s.t. \quad & .51 \leq F_{E85} \leq .85
\end{aligned}$$

The E85 blender's first order conditions:

$$P_{E85} = \big[F_{E85}(P_{E100}-P_{R6}) + (1-F_{E85})(P_{E0}+\rho P_{RIN})\big]\nu_{G1}+\nu_{G2} \tag{B.9}$$

$$P_{E100}-P_{R6} = P_{E0}+\rho P_{RIN} \quad \text{or} \quad F_{E85}=.51 \quad \text{or} \quad F_{E85}=.85 \tag{B.10}$$

B.2.2 Diesel Blenders

The diesel blender's maximization problem:

$$\max_{Q_{BX},F_{BX}} \quad Q_{BX}\Big(\big[P_{BX} - F_{BX}(P_{B100} - P_{R4}) - (1 - F_{BX})(P_{B0} + \rho P_{RIN})\big]\nu_{B1} + \nu_{B2}\Big)$$

The diesel blender's first order conditions:

$$P_{BX} = \big[F_{BX}(P_{B100} - P_{R4}) + (1 - F_{BX})(P_{B0} + \rho P_{RIN})\big]\nu_{B1} + \nu_{B2} \tag{B.11}$$

$$P_{B100} - P_{R4} = P_{B0} + \rho P_{RIN} \tag{B.12}$$

B.3 Producers

B.3.1 Ethanol and nonfuel corn

The corn producer's maximization problem:

$$\max_{Q_C,Q_{E100}} \quad P_C Q_C + (P_{E100} - \nu_C)Q_{E100} - \theta_C \frac{(Q_C + \mu Q_{E100})^{1+\frac{1}{\eta C}}}{1 + \frac{1}{\eta C}}$$

The corn producer's first order conditions:

$$P_C = \theta_C(Q_C + \mu Q_{E100})^{\frac{1}{\eta C}} \tag{B.13}$$

$$P_{E100} - \nu_C = \theta_C \mu (Q_C + \mu Q_{E100})^{\frac{1}{\eta C}} \tag{B.14}$$

Combining equations (B.13) and (B.15) yields a more convenient equation relating the price of ethanol and nonfuel corn.

$$P_{E100} = \mu P_C + \nu_C \tag{13a}$$

B.3.2 Sugarcane ethanol

The sugarcane ethanol importer's maximization problem:

$$\max_{Q^S_{E100}} \quad P^S_{E100}Q^S_{E100} - \nu_S Q^S_{E100} - \theta_S \frac{(Q^S_{E100})^{1+\frac{1}{\eta S}}}{1 + \frac{1}{\eta S}}$$

The interepretation of Q^S_{E100} is the *net imports* of Brazilian sugarcane ethanol. If the price of advanced RINs exceeds the price of renewable RINs by more than the cost of transporting ethanol to and from Brazil, then an arbitrageur could export corn ethanol and import sugarcane ethanol. The model permits such trade but does not keep track of gross flows. Knowing domestic corn ethanol production and net sugarcane imports is sufficient for determining the effect on the market for blended fuels. The sugarcane ethanol importer's first order condition:

$$P^S_{E100} = \nu_S + \theta_S(Q^S_{E100})^{\frac{1}{\eta S}} \tag{B.15}$$

B.3.3 Biodiesel

The biodiesel refiner's maximization problem:

$$\max_{Q_{B0}} \quad P_{B100}Q_{B100} - \nu_B Q_{B100} - \theta_B \frac{Q_{B100}^{1+\frac{1}{\eta B}}}{1+\frac{1}{\eta B}}$$

The biodiesel refiner's first order condition:

$$P_{B100} = \nu_B + \theta_B Q_{B100}^{\frac{1}{\eta B}} \tag{B.16}$$

B.3.4 Petroleum gasoline

The petroleum gasoline refiner's maximization problem:

$$\max_{Q_{E0}} \quad P_{E0}Q_{E0} - \theta_G \frac{Q_{E0}^{1+\frac{1}{\eta G}}}{1+\frac{1}{\eta G}}$$

The petroleum gasoline refiner's first order condition:

$$P_{E0} = \theta_G Q_{E0}^{\frac{1}{\eta G}} \tag{B.17}$$

B.3.5 Petroleum diesel

The petroleum diesel refiner's maximization problem:

$$\max_{Q_{B0}} \quad P_{B0}Q_{B0} - \theta_D \frac{Q_{B0}^{1+\frac{1}{\eta D}}}{1+\frac{1}{\eta D}}$$

The petroleum diesel refiner's first order condition:

$$P_{B0} = \theta_D Q_{B0}^{\frac{1}{\eta D}} \tag{B.18}$$

B.4 Market clearing conditions

The market clearing condition for ethanol:

$$F_{E10}Q_{E10} + F_{E85}Q_{E85} = Q_{E100} + Q_{E100}^S \tag{B.19}$$

The market clearing condition for BOB:

$$(1 - F_{E10})Q_{E10} + (1 - F_{E85})Q_{E85} = Q_{E0} \tag{B.20}$$

The market clearing condition for biodiesel:

$$F_{BX}Q_{BX} = Q_{B100} \tag{B.21}$$

The market clearing condition for petroleum diesel:

$$(1 - F_{BX})Q_{BX} = Q_{B0} \tag{B.22}$$

The market clearing condition for renewable RINs:

$$Q_{E100} + Q^S_{E100} + 1.5Q_{B100} = \Delta R4 + \Delta R5 + \Delta R6 + (Q_{E0} + Q_{B0})(\rho_3 + \rho_4 + \rho_5 + \rho_6) \tag{B.23}$$

Recall that Q^S_{E100} is net imports of sugarcane ethanol. The market clearing condition for advanced RINs:

$$Q^S_{E100} + 1.5Q_{B100} = \Delta R4 + \Delta R5 + (Q_{E0} + Q_{B0})(\rho_3 + \rho_4 + \rho_5) \tag{B.24}$$

The preceding condition is slack does not need to hold if the price of advanced RINs exceeds the price of renewable RINs by a sufficient margin. The market clearing condition for biodiesel RINs:

$$1.5Q_{B100} \geq \Delta R4 + (Q_{E0} + Q_{B0})(\rho_4) \tag{B.25}$$

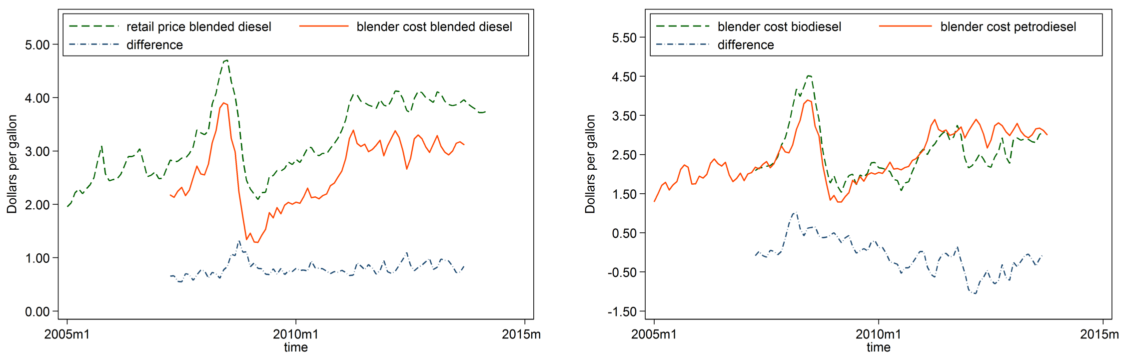
C Online Empirical Appendix [Not for publication]

This appendix extends the E10 analysis in section 4 to E85 and blended diesel. I use the convention $\Delta X_t = X_t - X_{t-1}$.

C.1 Price and blender cost of diesel

The model predicts that the retail price of blended diesel will equal the blender cost (BC) of components.

Figure 9: Diesel retail price and blender cost



Note: The left graph compares the retail price of diesel with the blender cost of diesel. The right graph compares the blender cost of biodiesel with the blender cost of petroleum-based diesel. Retail price is diesel fuel retail price including taxes, U.S. average, from EIA's Short Term Energy Outlook. Blender cost (BC) is calculated according to the following equation: $BC_{BX} = F_{BX}(P_{B100} - P_{R4}) + (1 - F_{BX})(P_{B0} + \rho P_{RIN})$. Biodiesel fraction F_{BX} is computed from the biodiesel quantity and diesel quantity reported in EIA's Short Term Energy Outlook. Biodiesel price P_{B100} is B-100 frieght on board at Illinois, Indiana and Ohio, from U.S. Bioenergy Statistics. The vector of RIN prices P_{RIN} includes renewable P_{R6}, advanced P_{R5}, and biodiesel P_{R4} RIN prices, from Bloomberg. Petroleum-based diesel price P_{B0} is Los Angeles ultra-low sulfur CARB diesel spot price, from EIA. The vector of RFS fractions ρ is from past EPA rules.

Figure 9 plots diesel retail price and blender cost of components. Like E10, the two series track each other closely and the retail price exceeds blender cost by a substantial margin, which I attribute to transportation costs and taxes. When I simulate the model, I add a wedge between the retail price and the blender cost. I allow the wedge to include an ad valorem component ν_{B1} and a per unit component ν_{B2} because some taxes are ad valorem and others are expressed per unit volume. The equation is $RP_{BX} = BC_{BX}\nu_{B1} + \nu_{B2}$. I estimate both components empirically, and use the estimates for calibrating the model.

The parameter ν_{B2} expresses a constant markup per gallon. To estimate the constant markup per gallon ν_{B2}, I regress the retail price of blended diesel on the blender cost of components.[39] Table 8 shows that the retail price exceeds the blender cost of components by about 81 cents. I use this estimate for the parameter ν_{B2} in simulations.

The parameter ν_{B1} expresses the passthrough of blender costs to the retail price of blended diesel. As with E10, I regress retail price on a distributed lag of the blender cost. Table 9 shows the results

[39] The equation is: $RP_{BX,t} = \nu_{B2} + \beta_1 BC_{BX,t} + u$.

Table 8: Regression of retail price of diesel on blender cost of diesel

BC_{BX}	0.997***
	(0.0247)
Constant	0.809***
	(0.0666)
Observations	78
R-squared	0.956

Standard errors in parentheses
*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

Note: This table reports regression results of retail price on blender cost of blended diesel using monthly data. See note on Figure 9.

Table 9: Effect of blender cost of diesel on retail price of diesel

$\Delta\Delta.BC_{BX,t}$	0.579***
	(0.0374)
$\Delta\Delta BC_{BX,t-1}$	0.944***
	(0.0417)
$\Delta\Delta BC_{BX,t-2}$	0.972***
	(0.0448)
$\Delta\Delta BC_{BX,t-3}$	1.011***
	(0.0517)
$\Delta\Delta BC_{BX,t-4}$	1.026***
	(0.0546)
$\Delta BC_{BX,t-5}$	1.074***
	(0.0583)
Constant	0.000627
	(0.00701)
Observations	72
R-squared	0.909

Standard errors in parentheses
*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

Note: This table reports regression results of a change in retail price on a distributed lag of blender cost of blended diesel using monthly data. See note on Figure 9.

of the regression.[40] A price change in the blender cost of components is followed by a price change in the retail price of blended diesel. I use the five-month estimate that 107% of a change to the blender cost of components is reflected in the retail price for the parameter ν_{B1} in simulations.

The model predicts that the blender cost of biodiesel will equal the blender cost of petroleum-based diesel whenever the blend fraction is interior, i.e. between 0% and 5%. Figure 9 shows that the prices of the two components track each other closely.

[40]The regression equation is $\Delta RP_{BX,t} = \beta_0 + \sum_{i=0}^{2} \beta_{i-1} \Delta\Delta BC_{BX,t-i} + \nu_{B1} \Delta BC_{BX,t-3} + u$.

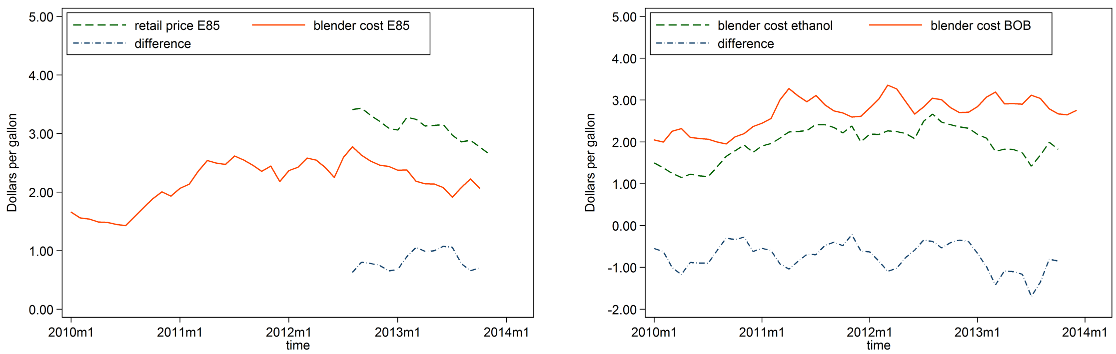
C.2 Price and blender cost of E85

The model predicts that the retail price of E85 will equal the blender cost (BC) of components:

$$BC_{E85} = F_{E85}(P_{E100} - P_{R6}) + (1 - F_{E85})(P_{E0} + \rho P_{RIN})$$

Whereas the model was augmented with octane-boosting additives for the empirical analysis of E10, there is no need to do that for E85 because E85 has high octane content without additives.

Figure 10: E85 retail price and blender cost



Note: The left graph compares the retail price of E85 with the blender cost of E85. The right graph compares the blender cost of ethanol with the blender cost of BOB. Retail price is the U.S. city average retail price of unleaded regular gasoline, from EIA. Blender cost (BC) is calculated according to the following equation: $BC_{E85} = F_{E85}(P_{E100} - P_{R6}) + (1 - F_{E85})(P_{E0} + \rho P_{RIN})$. I assume the ethanol fraction F_{E85} is 71%, the average blend reported by EIA. Ethanol price P_{E100} is blender cost of ethanol with credit, from U.S. Bioenergy Statistics. The vector of RIN prices P_{RIN} includes renewable P_{R6}, advanced P_{R5}, and biodiesel P_{R4} RIN prices, from Bloomberg. BOB price P_{E0} is generic RBOB gasoline (XB1), from Bloomberg. The vector of RFS fractions ρ is from past EPA rules.

Figure 10 shows that the retail price of E85 exceeds the blender cost of components. As with E10, I regress the retail price of E85 on the blender cost of components.[41] Table 10 shows that the retail price exceeds the blender cost of components by about \$1.75. However, the sample period is short, so in simulations I use the E10 estimate of markup per gallon ($\nu_{G2} = 0.72$).

As with E10, I regress retail price on a distributed lag of the blender cost. Table 11 shows the results of the regression.[42] These estimates are not precise, so in simulations I use the E10 estimate of passthrough of blender costs ($\nu_{G1} = 1.09$).

[41] The equation is: $RP_{E85,t} = \nu_{G2} + \beta_1 BC_{E85,t} + u$.

[42] The regression equation is $\Delta RP_{E85,t} = \beta_0 + \sum_{i=0}^{2} \beta_{i-1} \Delta\Delta BC_{E85,t-i} + \nu_{G1} \Delta BC_{E85,t-3} + u$.

Table 10: Regression of retail price of E85 on blender cost of E85

$BC_{E85,t}$	0.601***
	(0.151)
Constant	1.751***
	(0.348)
Observations	15
R-squared	0.550

Standard errors in parentheses
*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

Note: This table reports regression results of retail price on blender cost of E85 using monthly data. See note on Figure 10.

Table 11: Effect of blender cost of E85 on retail price of E85

$\Delta\Delta BC_{E85,t}$	0.247
	(0.331)
$\Delta\Delta BC_{E85,t-1}$	0.519
	(0.463)
$\Delta\Delta BC_{E85,t-2}$	0.497
	(0.558)
$\Delta BC_{E85,t-3}$	0.413
	(0.666)
Constant	-0.0289
	(0.0376)
Observations	14
R-squared	0.196

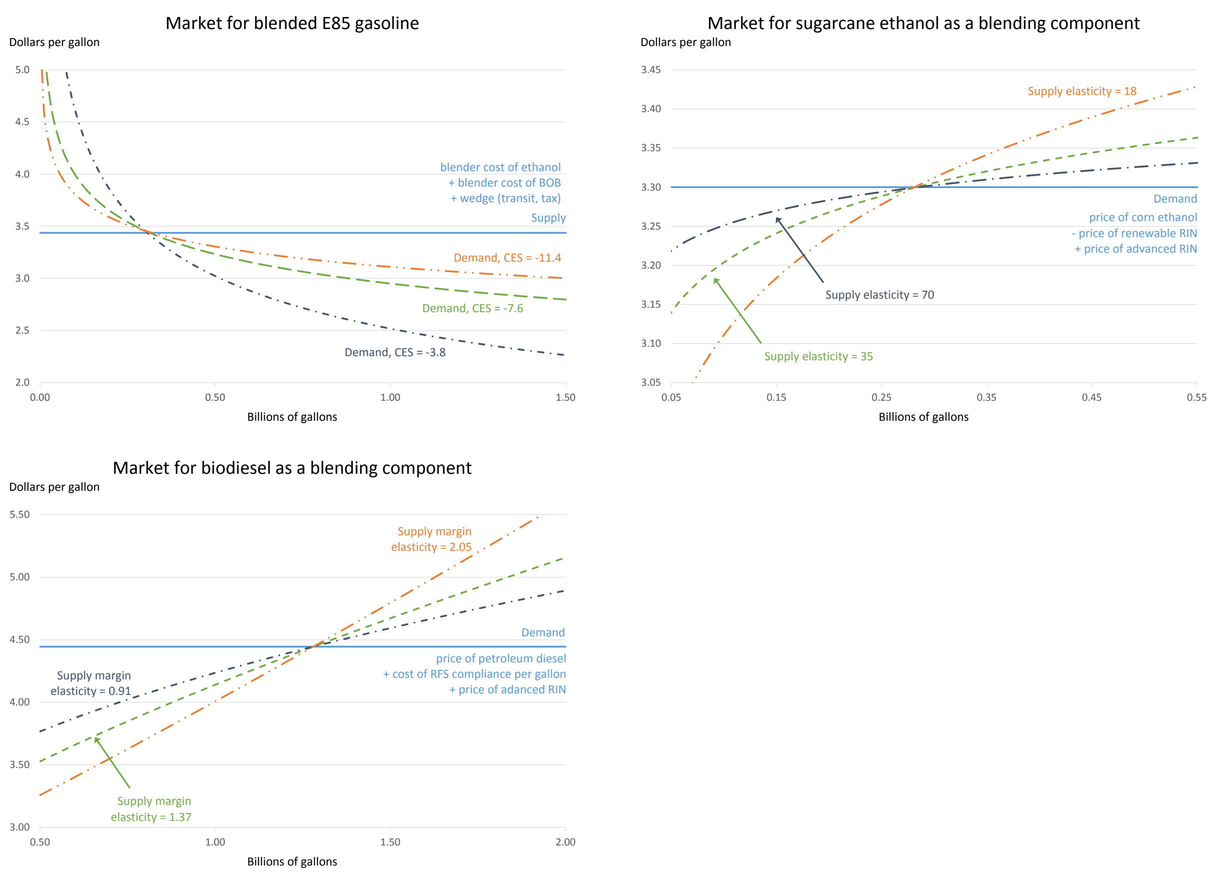
Standard errors in parentheses
*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

Note: This table reports regression results of a change in retail price on a distributed lag of blender cost of E85 using monthly data. See note on Figure 10.

D Online Calibration Appendix [Not for publication]

The two parameters that determine demand for E85 are the elasticity of substitution $\frac{\sigma}{1-\sigma}$ and the E10 demand share α. The main results are reported for an elasticity of -7.6, and results are calculated for elasticities 50% higher and lower as well, -3.8 and -11.4. For each elasticity, α is calculated such that the E85 demand curve passes through 300 million gallons at a price of \$3.50. For elasticities of -3.8, -7.6, and -11.4, the demand shares are .95, .80, and .59. Holding fixed the ethanol fraction in E85 and the quantity and price of E10, the implied demand curves for E85 at various elasticities of substitution are shown in Figure 11.

Figure 11: Alternative biofuel supply and demand elasticities



Note: These graphs depict alternative assumptions about biofuel supply and demand elasticities. For E85, the elasticity of substitution with E10 takes on the values -3.8, -7.6, and -11.4. In each case, the demand share is adjusted such that the demand for E85 is 300 million gallons at \$3.40 per gallon. For sugarcane ethanol, the elasticity of supply takes on the values 18, 35, and 70, and the supply intercept is adjusted such that the supply of sugarcane ethanol is 280 million gallons at \$3.30 per gallon. For biodiesel, the elasticity of supply takes on the values 0.91, 1.37, and 2.05, and the demand intercept is adjusted such that the supply of biodiesel is 1.28 billion gallons at \$4.44 per gallon.

Pouliot and Babcock (2014) estimate E85 demand with various assumptions about the convenience cost of E85 and the strength of consumer preferences for regular gasoline. When the price of E85 is at the energy-equivalent parity price of E10, their estimates of E85 quantity demanded range from about 0.5 to 6.0 billion gallons, with the main cases near 2 billion gallons at parity.[43] Under nearly all preference assumptions, Pouliot and Babcock (2014) estimate that FFV drivers would be willing to consume as much as 8 billion gallons of E85 at a sufficiently large discount relative to E10. However, even though drivers might be willing to consume E85, Pouliot and Babcock find that the capacity constraints of existing E85 fueling stations could limit distribution to about 1.5 billion gallons. In other words, their estimates imply the binding constraint on consumption of E85 is the capacity of E85 fueling stations, not consumer demand or the number of FFVs.

My constant-elasticity-of-substitution specification of E85 demand is different from Pouliot and Babcock's, but the implications for E85 demand are largely consistent. In my base case with an elasticity of substitution equal to -7.6, the E85 quantity demanded at the energy-equivalent parity price of E10 is 1.3 billion gallons. This is a bit lower than most of Pouliot and Babcock's estimates of consumer demand but still within their estimates of fueling station capacity. In my high elasticity alternative case, the E85 quantity demanded at the energy-equivalent parity price of E10 is 2.7 billion gallons. This would be appropriate to consider if willingness to pay for E85 is relatively high and investment in new fueling stations is very responsive to the mandate. In my low elasticity alternative case, the E85 quantity demanded at the energy-equivalent parity price of E10 is 0.6 billion gallons. This would be appropriate to consider if willingness to pay for E85 was very low.

One shortcoming of my specification is that it does not capture the upper limit on E85 consumption. Even for very large price discounts, there would be some limit on the ability of FFVs to consume E85. The CES specification implies that greater price discounts will always lead to more consumption. However, this shortcoming is not empirically relevant in my simulations because E85 consumption remains below 1.5 billion gallons in all of the scenarios considered.

Table 12: Net imports of ethanol from Brazil to the United States

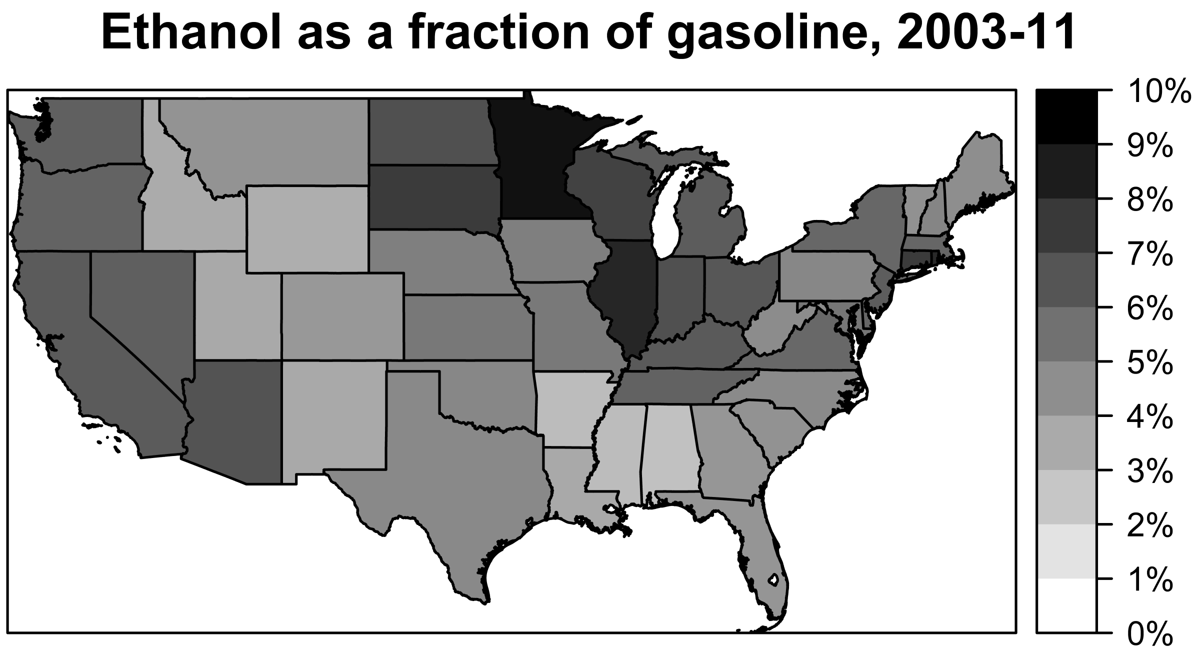
	Million gallons		
Year	**Imports**	**Exports**	**Net imports**
2010	0	23	-23
2011	101	396	-295
2012	404	86	318
2013	242	47	195

Source: Energy Information Administration `http://www.eia.gov/petroleum/data.cfm`.

To estimate the response to a change in the RFS fraction, I must make some assumption about the supply of sugarcane ethanol and biodiesel. The supply of sugarcane ethanol probably has a smaller impact because its price is tied to the price of corn ethanol. Recall that the different treatment by the RFS of corn ethanol and sugarcane ethanol creates a potential arbitrage opportunity. If the price of an advanced RIN is high enough relative to the price of a renewable RIN, an arbitrageur will export corn ethanol from the United States to Brazil and import sugarcane ethanol from Brazil to the United States. Table 11 shows net imports of ethanol from Brazil in 2012 and 2013 were 318 million gallons and 195 million gallons.

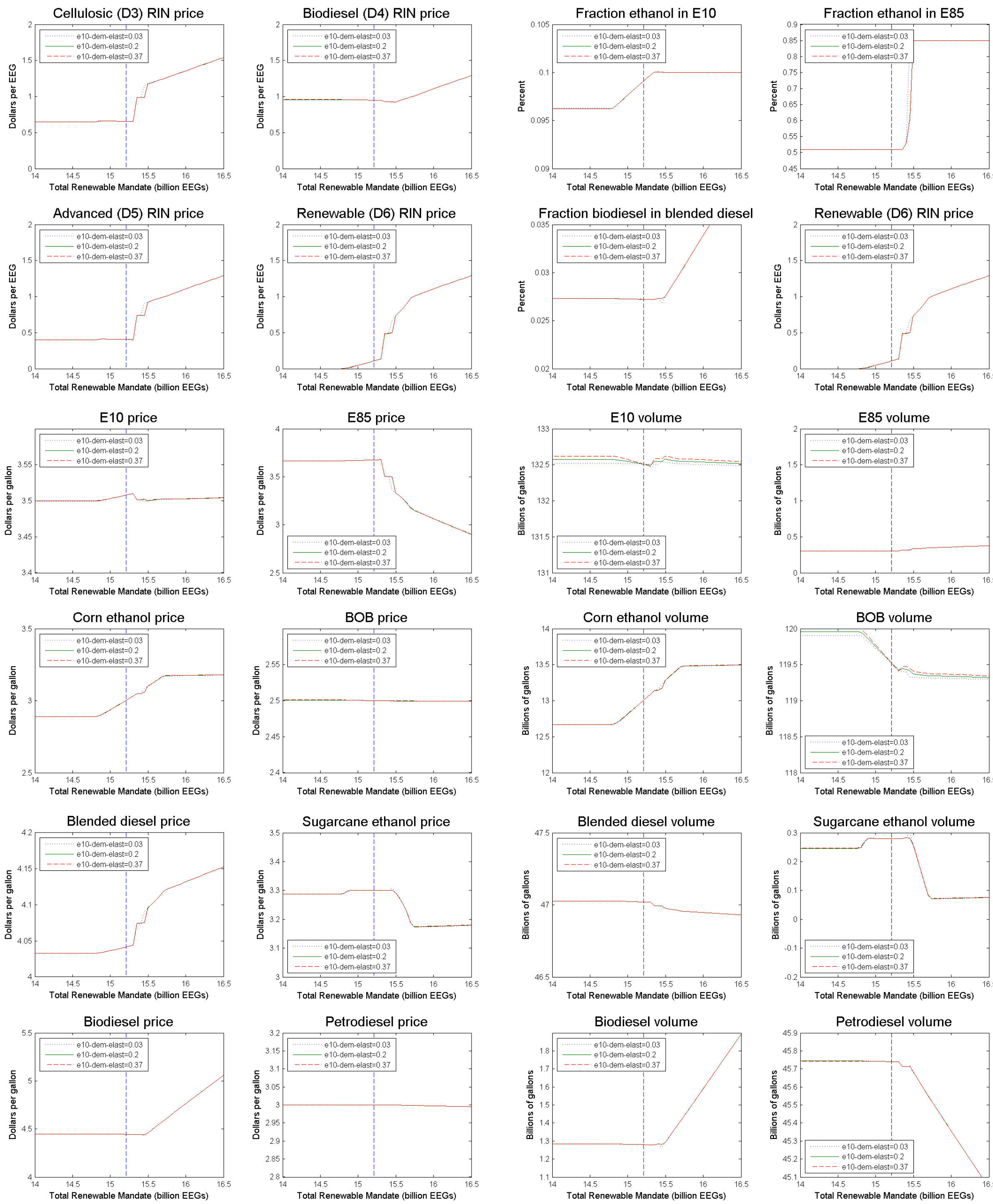
[43] Pouliot and Babcock (2014) figures 4 through 7.

Figure 12



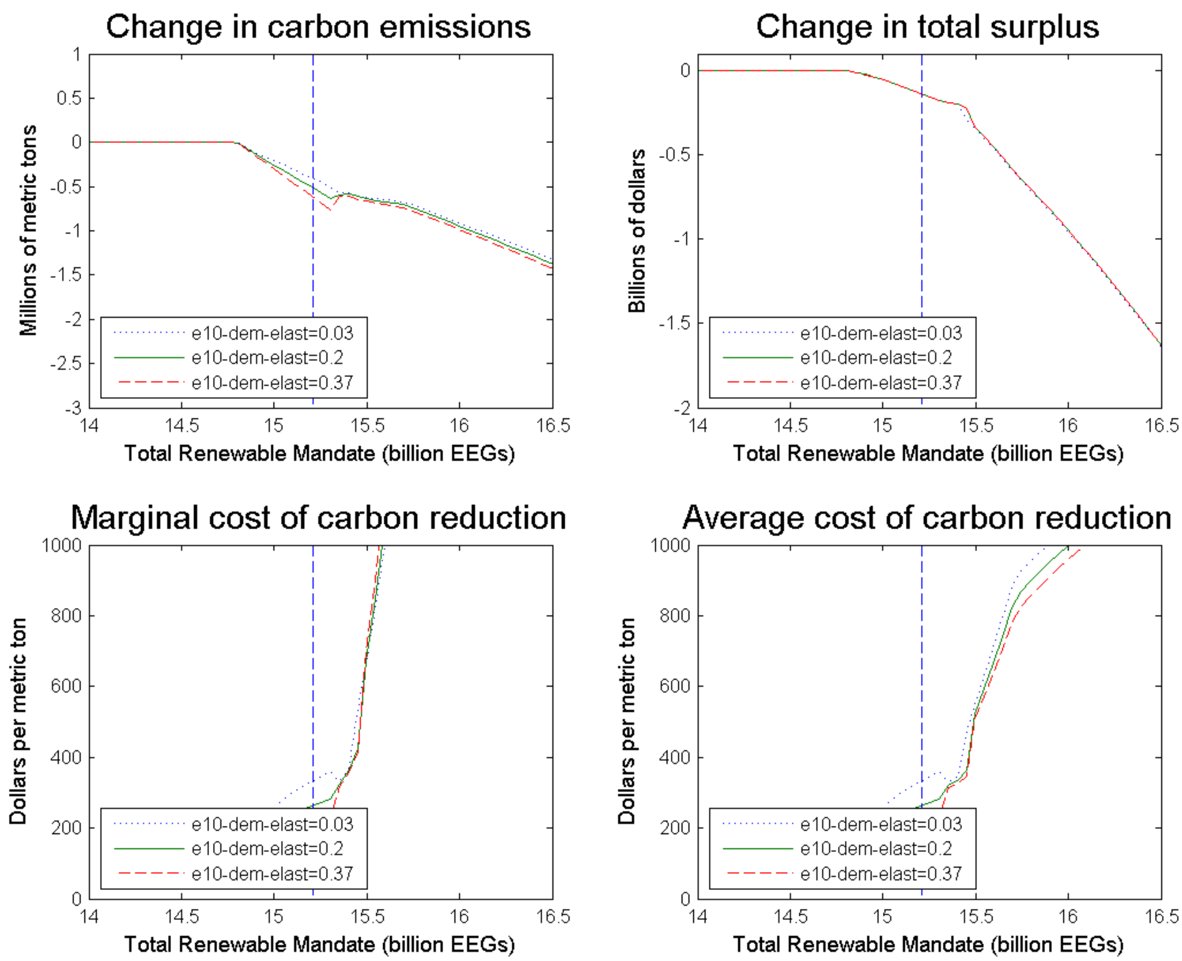
Note: States are shaded in proportion to the fraction of ethanol in blended gasoline from 2003 to 2011. Source data from Energy Information Agency State Energy Data System.

Figure 13: Simulation for three values of gasoline elasticity of demand



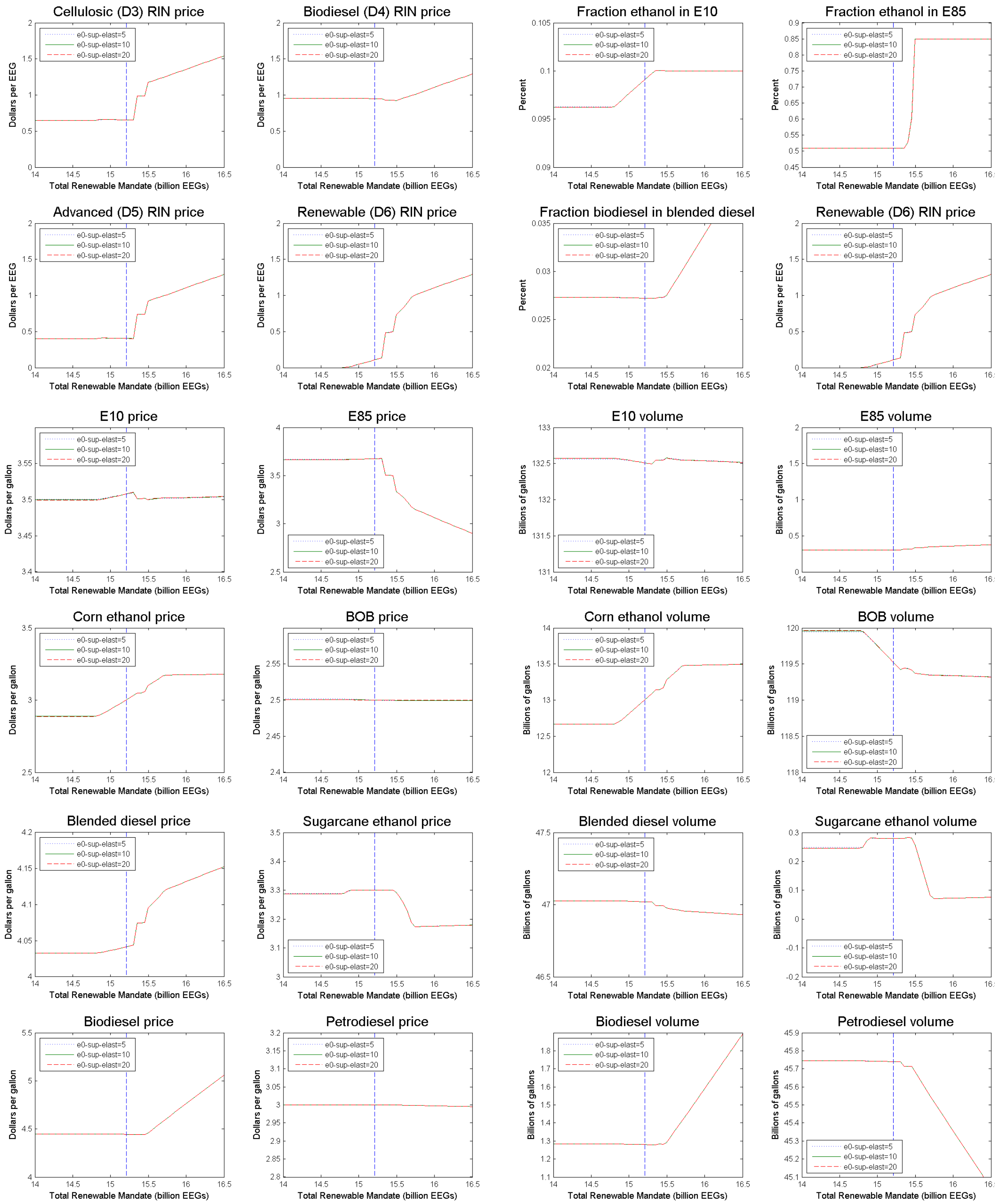
Note: These graphs depict the results of numerically solving the system of equations for many values for the renewable fuel mandate (14 to 16.5 billion ethanol equivalent gallons) and three values of gasoline elasticity of demand.

Figure 14: Emissions and welfare for three values of gasoline elasticity of demand



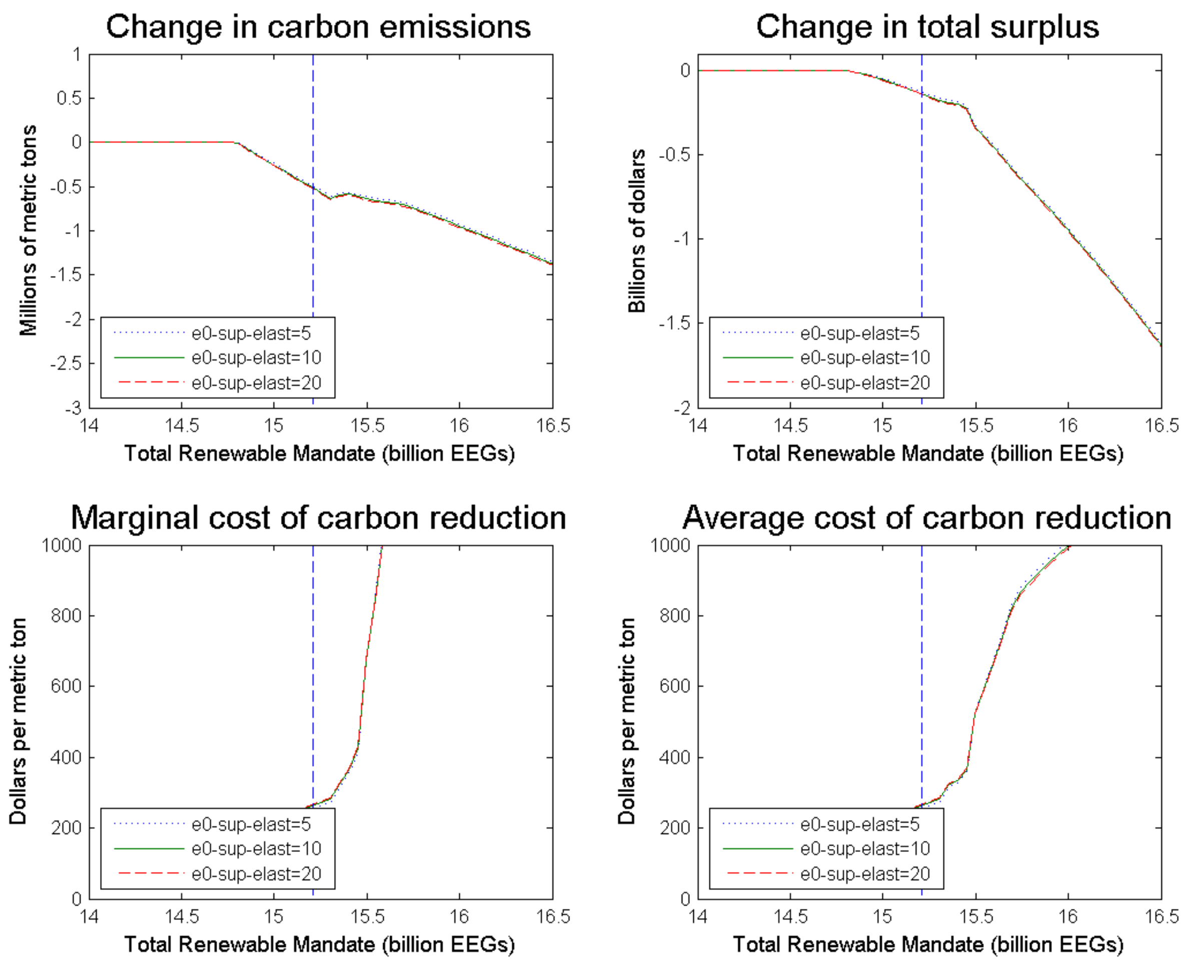
Note: To calculate total emissions, I multiply the consumption volume of the various blending components by their life cycle emissions. The change in total surplus is calculated using the model supply and demand curves.

Figure 15: Simulation for three values of BOB elasticity of supply



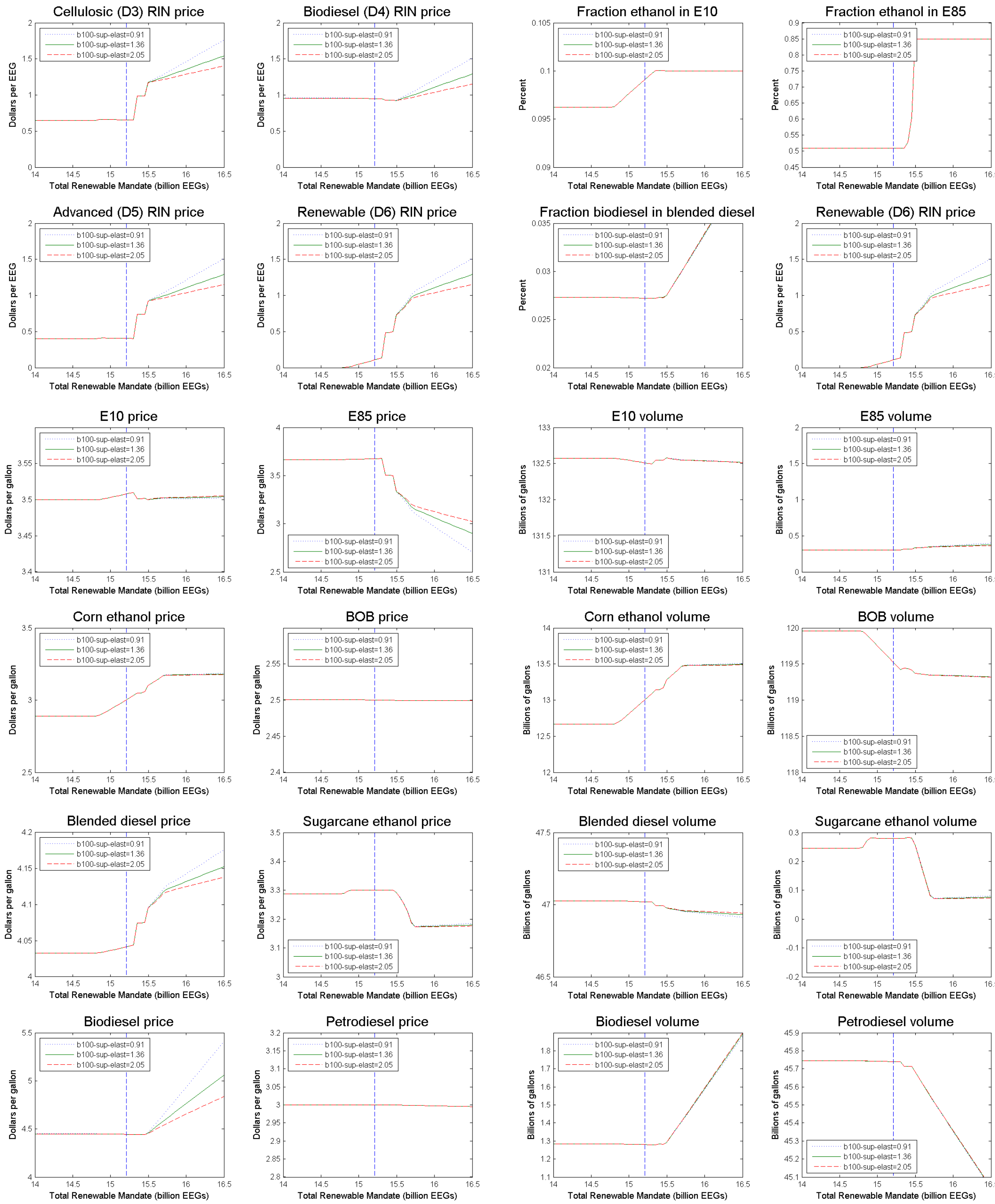
Note: These graphs depict the results of numerically solving the system of equations for many values for the renewable fuel mandate (14 to 16.5 billion ethanol equivalent gallons) and three values of BOB elasticity of supply.

Figure 16: Emissions and welfare for three values of BOB elasticity of supply



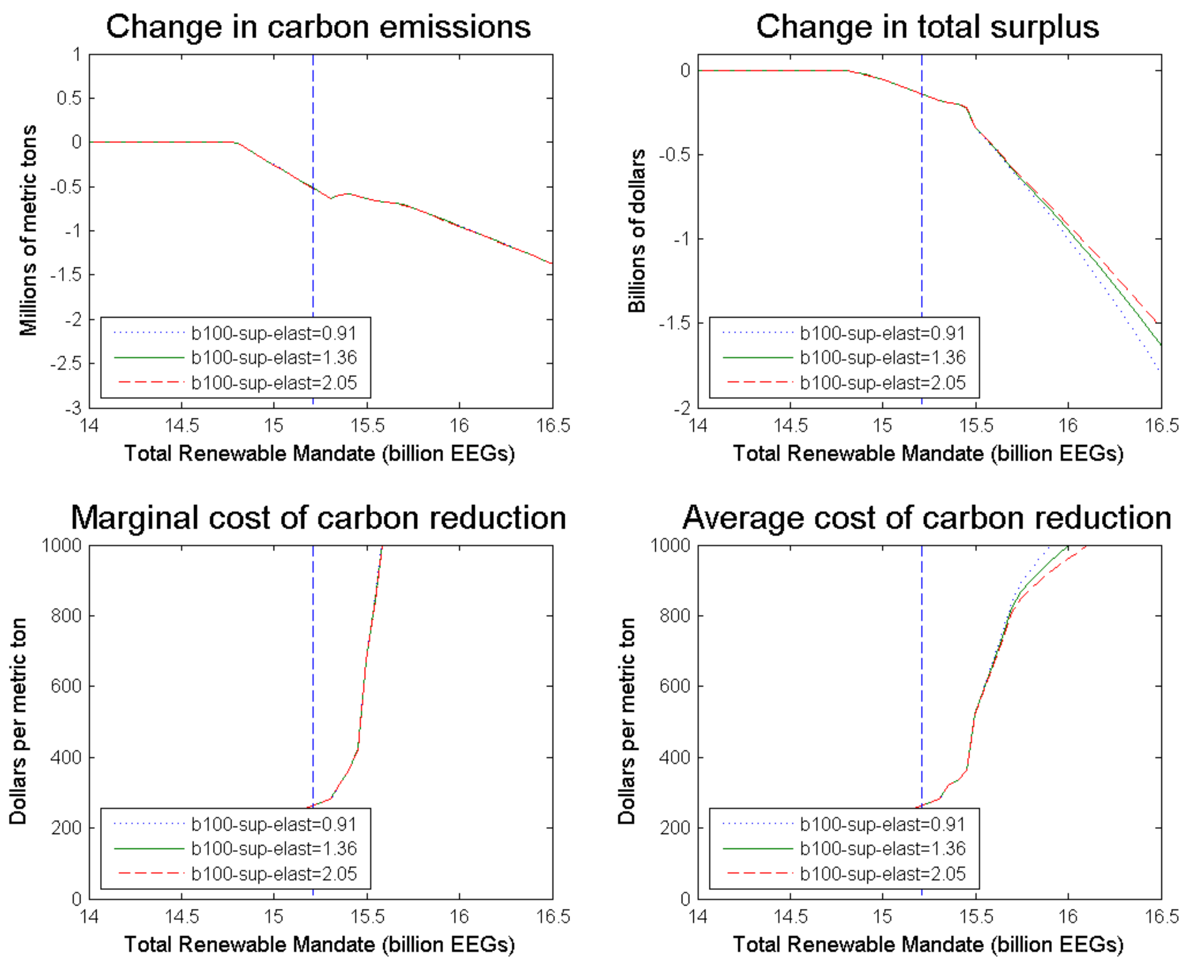
Note: To calculate total emissions, I multiply the consumption volume of the various blending components by their life cycle emissions. The change in total surplus is calculated using the model supply and demand curves.

Figure 17: Simulation for three values of biodiesel elasticity of supply



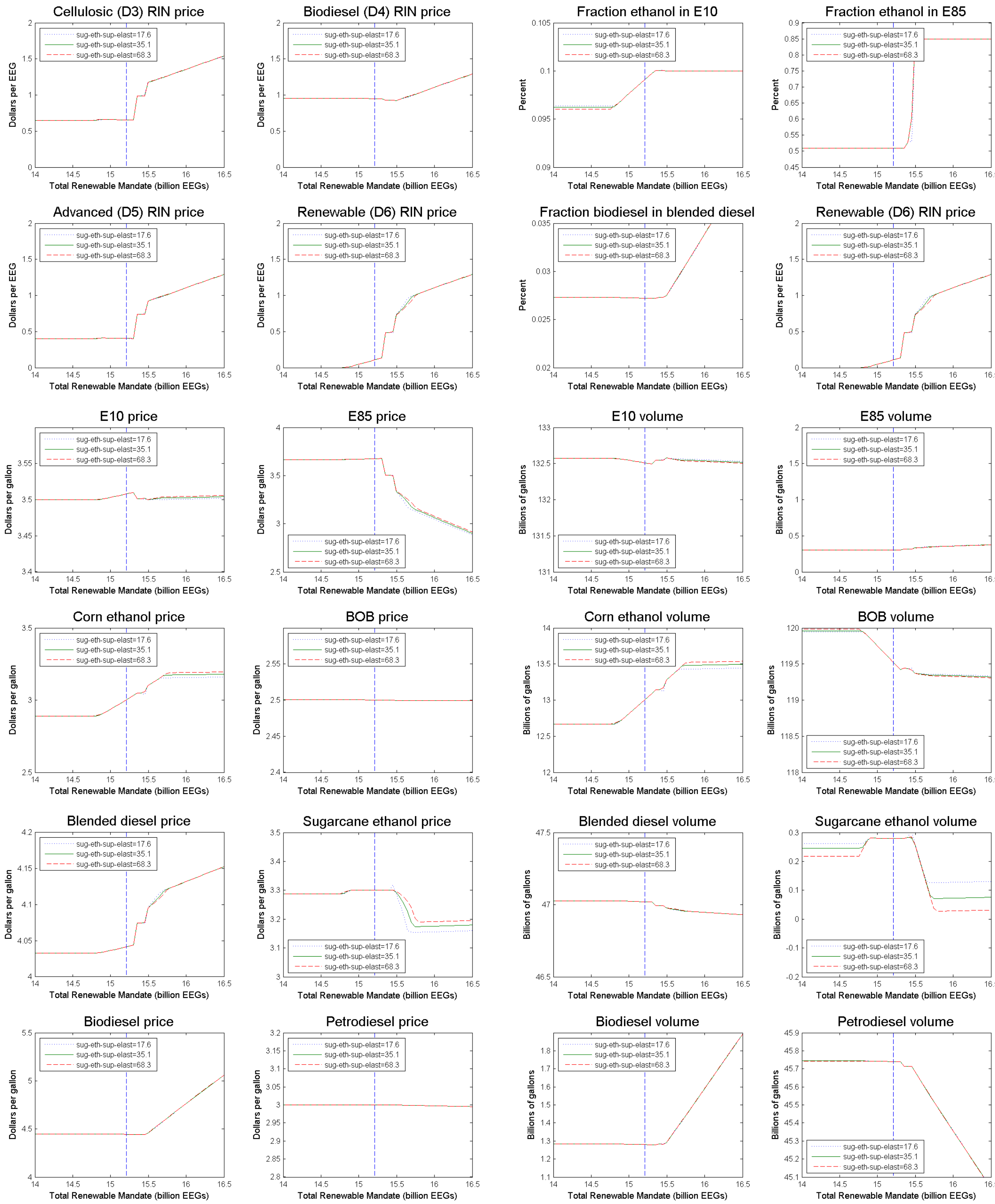
Note: These graphs depict the results of numerically solving the system of equations for many values for the renewable fuel mandate (14 to 16.5 billion ethanol equivalent gallons) and three values of biodiesel elasticity of supply.

Figure 18: Emissions and welfare for three values of biodiesel elasticity of supply



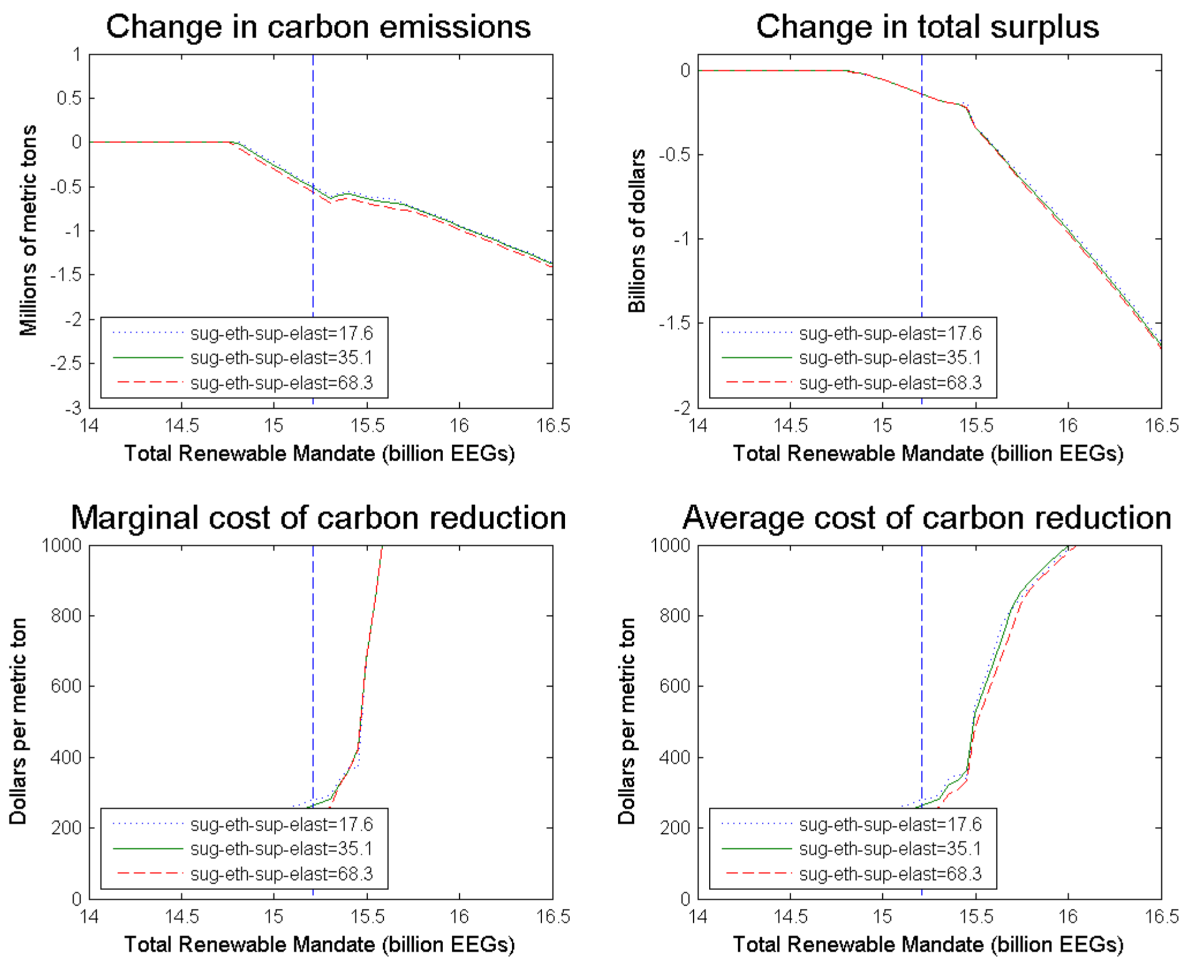
Note: To calculate total emissions, I multiply the consumption volume of the various blending components by their life cycle emissions. The change in total surplus is calculated using the model supply and demand curves.

Figure 19: Simulation for three values of sugarcane ethanol elasticity of supply



Note: These graphs depict the results of numerically solving the system of equations for many values for the renewable fuel mandate (14 to 16.5 billion ethanol equivalent gallons) and three values of sugarcane ethanol elasticity of supply.

Figure 20: Emissions and welfare for three values of sugarcane ethanol elasticity of supply



Note: To calculate total emissions, I multiply the consumption volume of the various blending components by their life cycle emissions. The change in total surplus is calculated using the model supply and demand curves.